

# Search for New Physics with Jets in CMS

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- ❑ Large Hadron Collider
- ❑ Compact Muon Solenoid
- ❑ What is a Jet?
- ❑ Jets in CMS
- ❑ Jet calibration and Performance
- ❑ Recent Searches for New Physics with Jets
  - Search for quark compositeness with dijet angular distributions
  - Search for resonances in dijet angular ratio
  - Search for resonances in Dijet Mass Spectrum
  - Search for pair produced dijet resonances with four jets
- ❑ Conclusion and Outlook

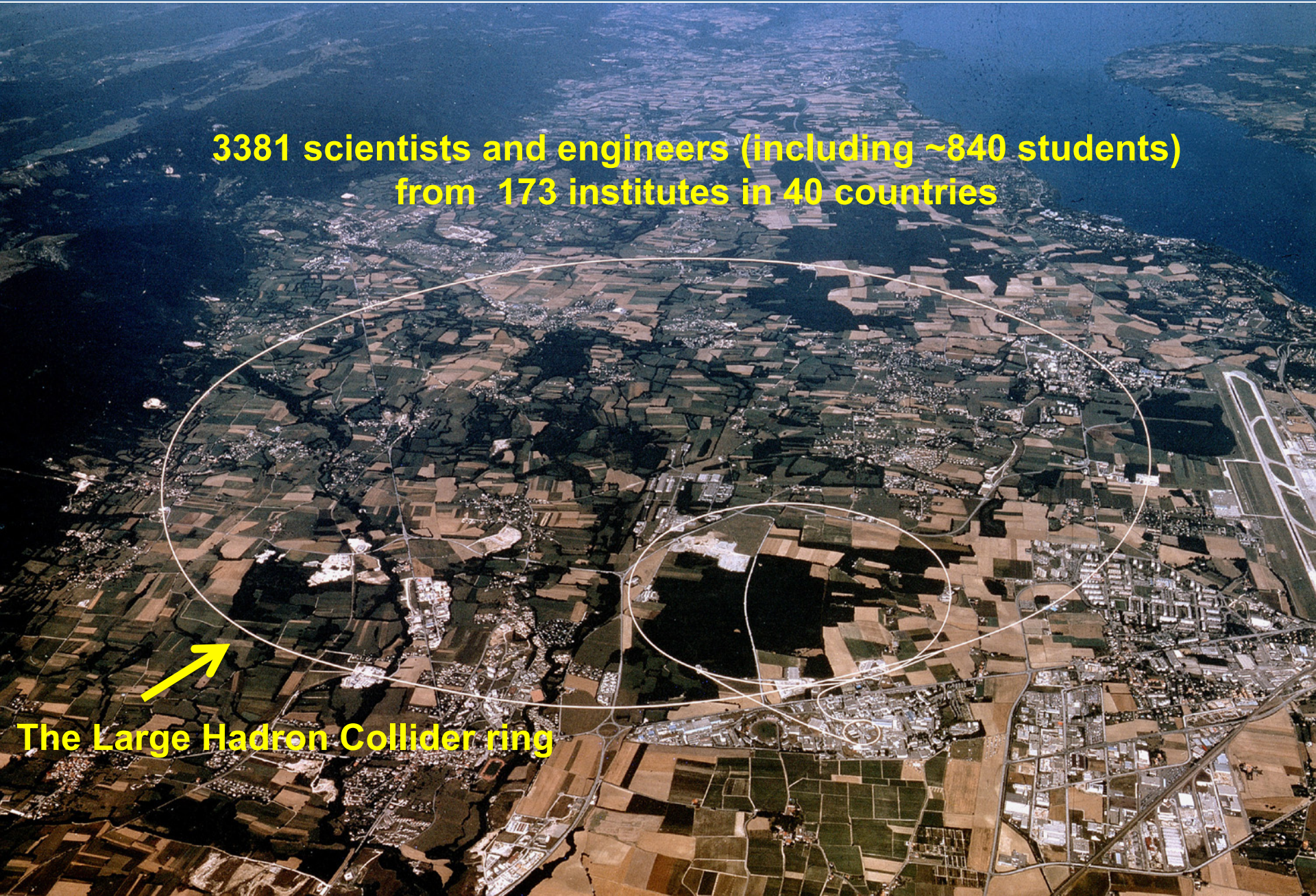


# CERN – European Centre for Nuclear Research

**3381 scientists and engineers (including ~840 students)  
from 173 institutes in 40 countries**



**The Large Hadron Collider ring**





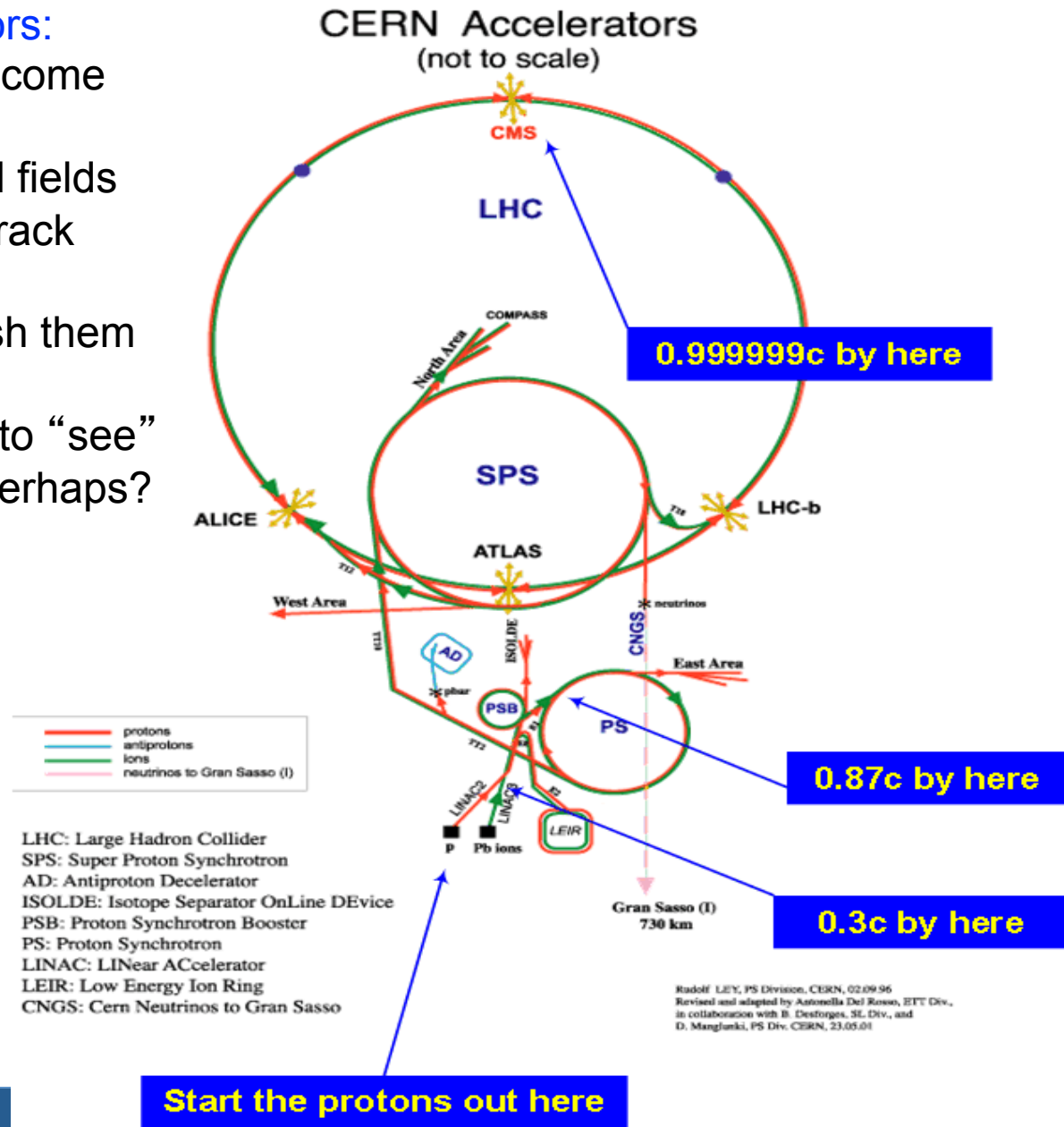
# CERN accelerator complex

## General concept of accelerators:

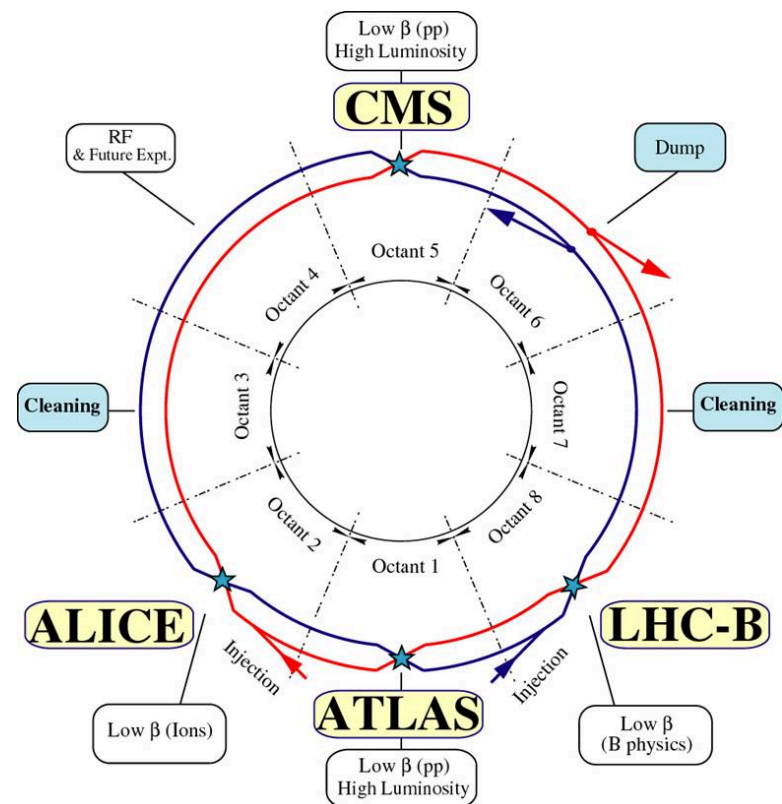
- Ionize some atoms so they become charged
- Speed them up using electrical fields
- Curve them in a manageable track using magnetic fields
- Once at sufficient speed, smash them into something!
- Have particle detectors handy to “see” what comes out. New particles perhaps?

## CERN Accelerator:

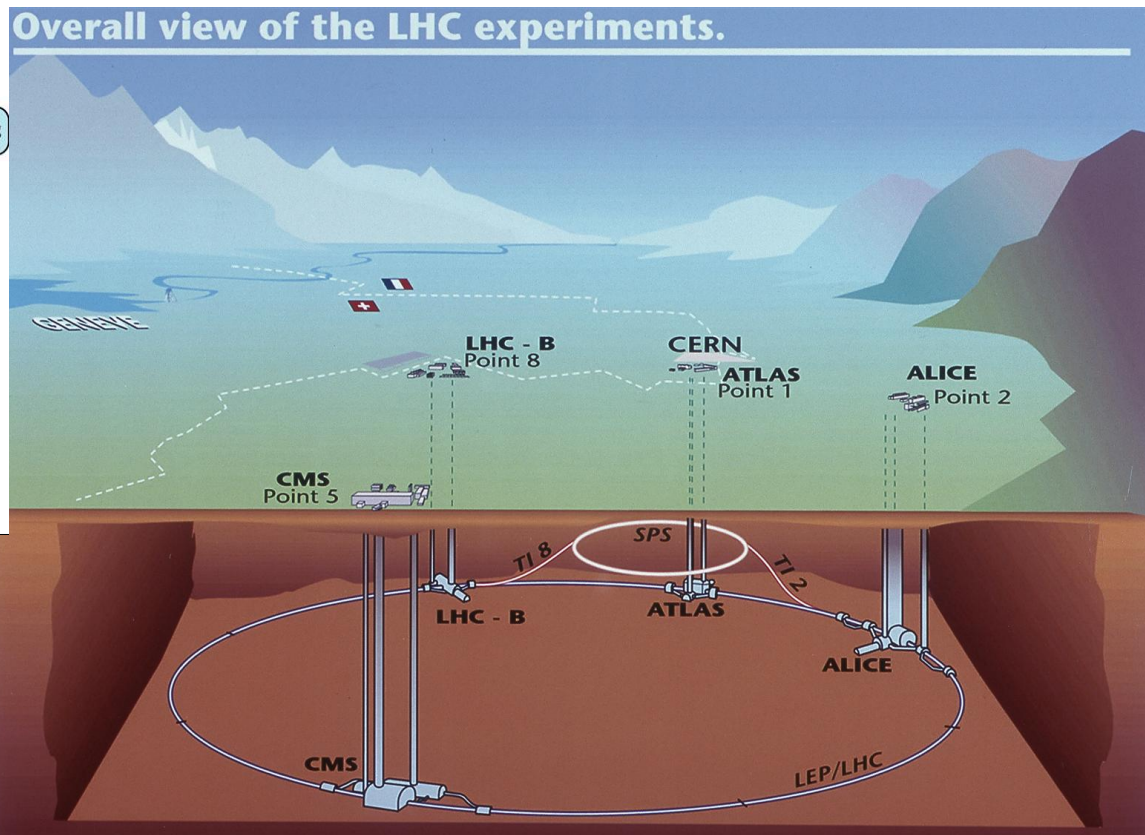
- A Proton Source
- Radio Freq Quadrupole (750 keV)
- LINAC2 (50 MeV)
- PS Booster (1.4 GeV)
- PS (25 GeV)
- SPS (450 GeV)
- LHC (7 TeV)



# The LHC ring and its detectors



Overall view of the LHC experiments.



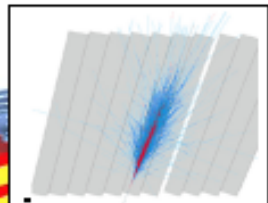
□ 100 m below the surface | 27 km in circumference

# CMS: Compact Muon Solenoid

## SUPERCONDUCTING COIL

Total weight : 12,500 t  
Overall diameter : 15 m  
Overall length : 21.6 m  
Magnetic field : 4 Tesla

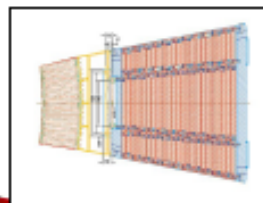
ECAL Scintillating  $\text{PbWO}_4$  Crystals



## CALORIMETERS

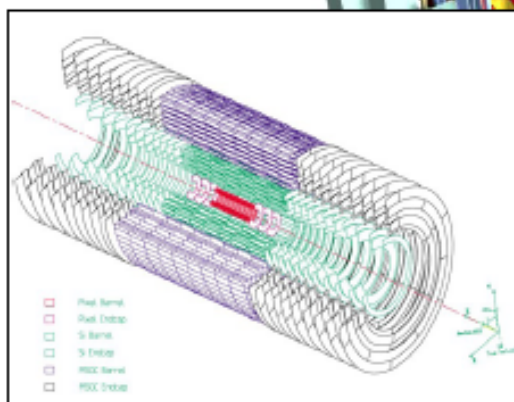
HCAL

brass Plastic scintillator sandwich



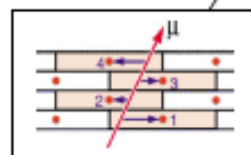
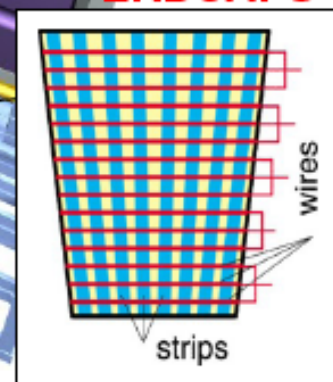
## IRON YOKE

## TRACKERS



Silicon Microstrips  
Pixels

## MUON ENDCAPS



Drift Tube  
Chambers (DT)



Resistive Plate  
Chambers (RPC)

## MUON BARREL

Cathode Strip Chambers (CSC)  
Resistive Plate Chambers (RPC)

# What is Luminosity?

Instantaneous luminosity is connected to the beam properties as:

$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F$$

no of particles per bunch (blue arrow) →  $N_b$   
 no of bunches per beam (orange arrow) →  $n_b$   
 frequency of revolution (red arrow) →  $f_{rev}$   
 geometric luminosity reduction factor due to a non-zero crossing angle (green arrow) →  $F$   
 normalized transverse emittance (blue arrow) →  $\epsilon_n$   
 beam amplitude factor at the collision point (red arrow) →  $\beta^*$

- The quantity often used in plots:

Integrated Luminosity:  $\int L dt$

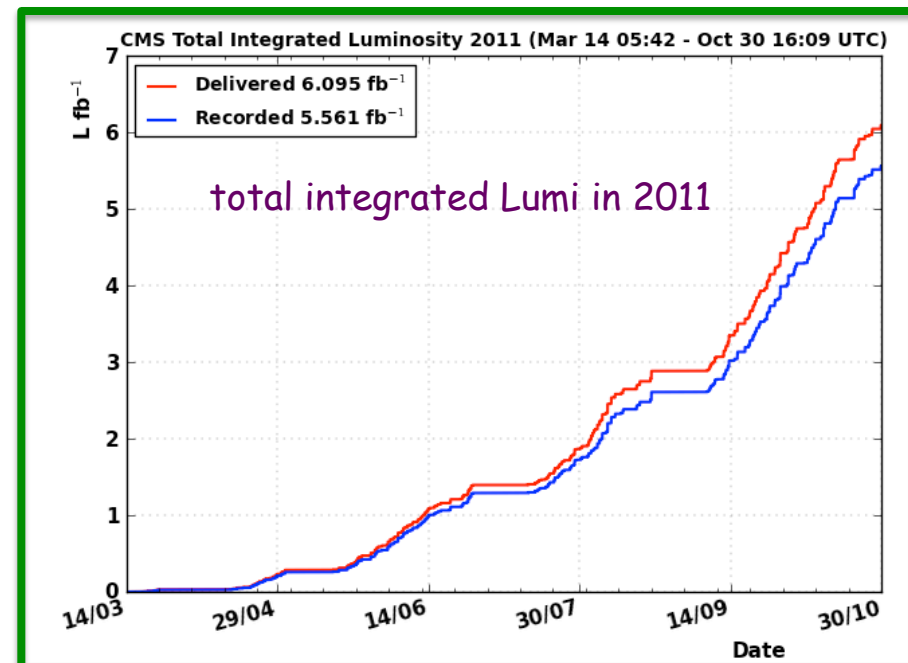
If Instantaneous Lumi  $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$   
 then after 1 year of running  
 Integrated Luminosity  $\sim 10 \text{ pb}^{-1}$

- The event rate for a process with cross section  $\sigma$  is:

$$N_{event} = L \sigma_{process}$$

[cross-section unit:

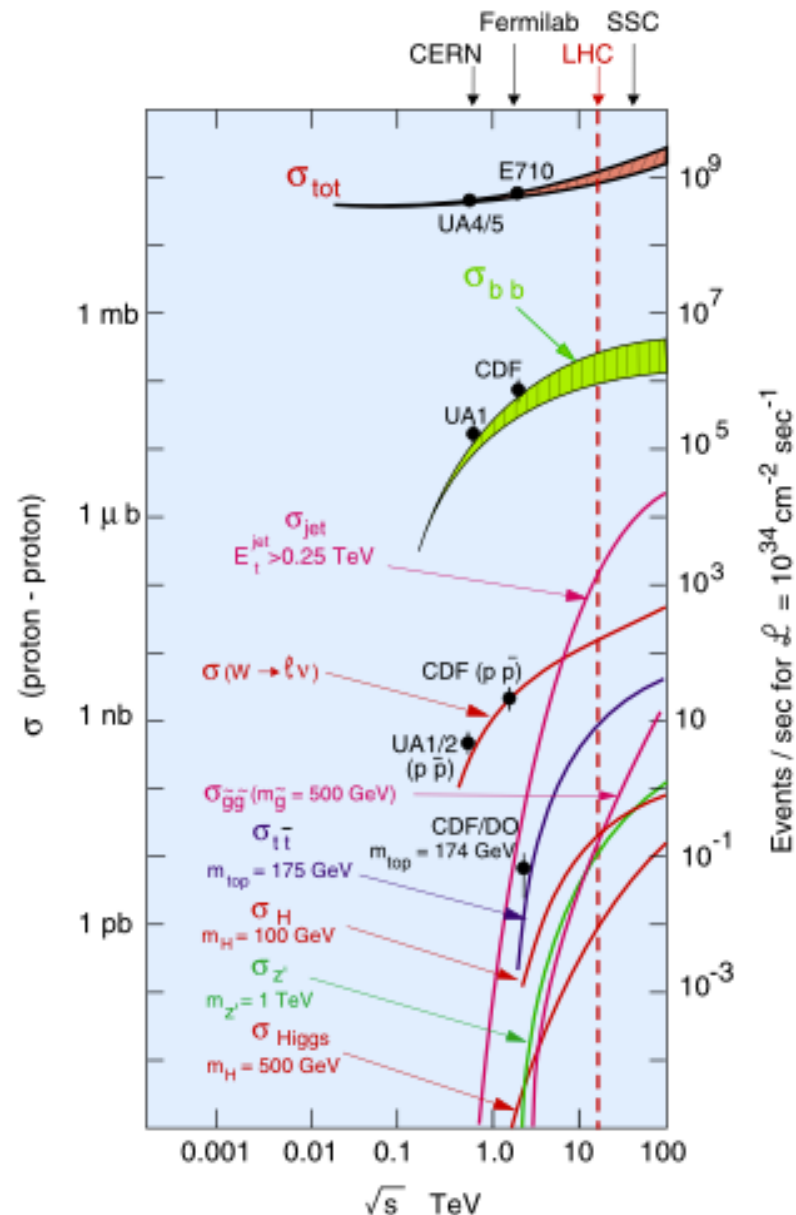
$$1 \text{ barn} = 10^{-28} \text{ m}^2 = 10^{-24} \text{ cm}^2]$$





# Jet Physics at the LHC

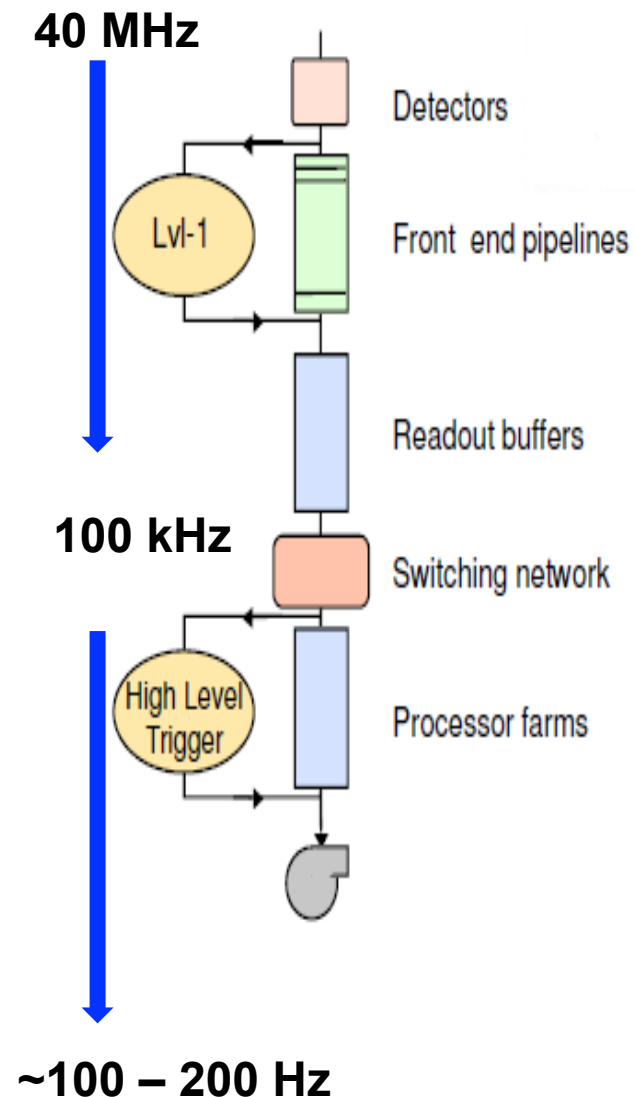
- Total cross section  $\sim 100\text{-}120\text{ mb}$
- The goal at startup was to re-establish the standard model (i.e., QCD, SM candles) in the LHC energy regime
- $\sigma(p_T > 250\text{ GeV})$   
100x higher than Tevatron
- Electroweak  
10x higher than Tevatron
- Top  
100x higher than Tevatron
- Jet measurements at LHC are important:
  - confront pQCD at the TeV scale
  - constrain Parton Distribution Functions
  - probe strong coupling constant
- Important backgrounds for SUSY and BSM searches
  - sensitive to new physics
    - quark substructure, excited quarks, dijet resonances, etc.
- QCD processes are not statistics limited!





# CMS Trigger System

- ❑ LHC will produce interactions at 40 MHz frequency, but only a small fraction of these events can be written on disk due to limitation in disk i/o capability.
- ❑ The vast majority of events produced is not interesting, because it involves low transferred momentum interactions (minimum bias events).
- ❑ A trigger system is needed to save interesting events at the highest possible rate.
- ❑ The expected rate of events written to disk is foreseen to be 100 Hz.
- ❑ Two-tiered system
  - L1: hardware, firmware
  - L2,L3 merged into HLT (high-level software)



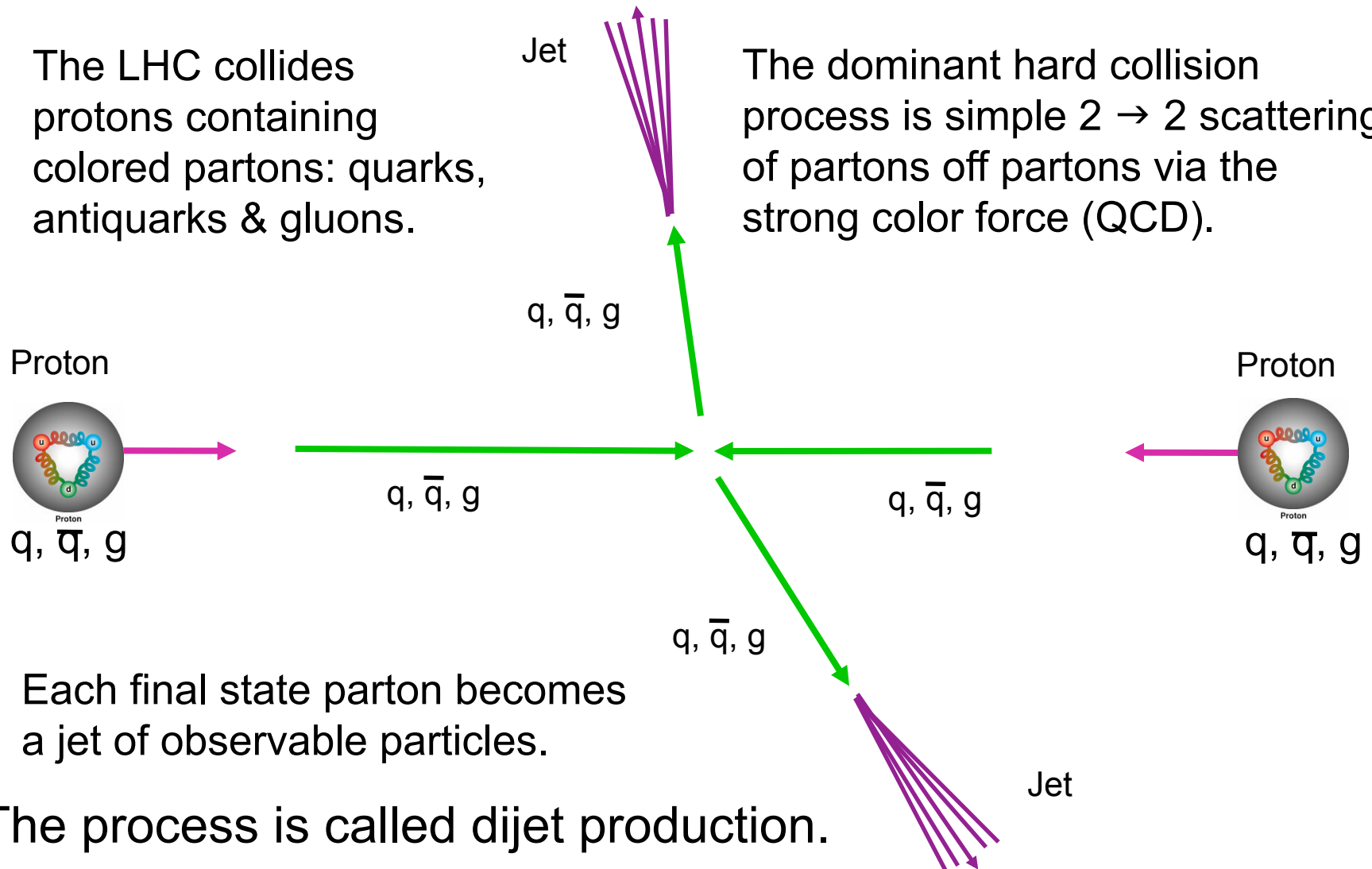
# Why should we care about jets?

- Jets are everywhere; their cross section is orders of magnitude higher than most other processes.
- Jets can fake as  $\gamma$ ,  $e$ ,  $\mu$ ,  $\tau$ 
  - Probability of jet faking a  $\gamma \sim 10^{-4}$
  - Probability of faking  $e/\mu \sim 10^{-5}$ , but some jets have real lepton, e.g., b-jets
  - Probability of faking a  $\tau \sim 10^{-3}$
- Light quark or gluon jets can fake b-quark jet at the % level
- Missing Transverse Energy must be corrected for jet energy measurements.
- If jets are not your signal they are most certainly your background !

# What are Jets?

The LHC collides protons containing colored partons: quarks, antiquarks & gluons.

The dominant hard collision process is simple  $2 \rightarrow 2$  scattering of partons off partons via the strong color force (QCD).

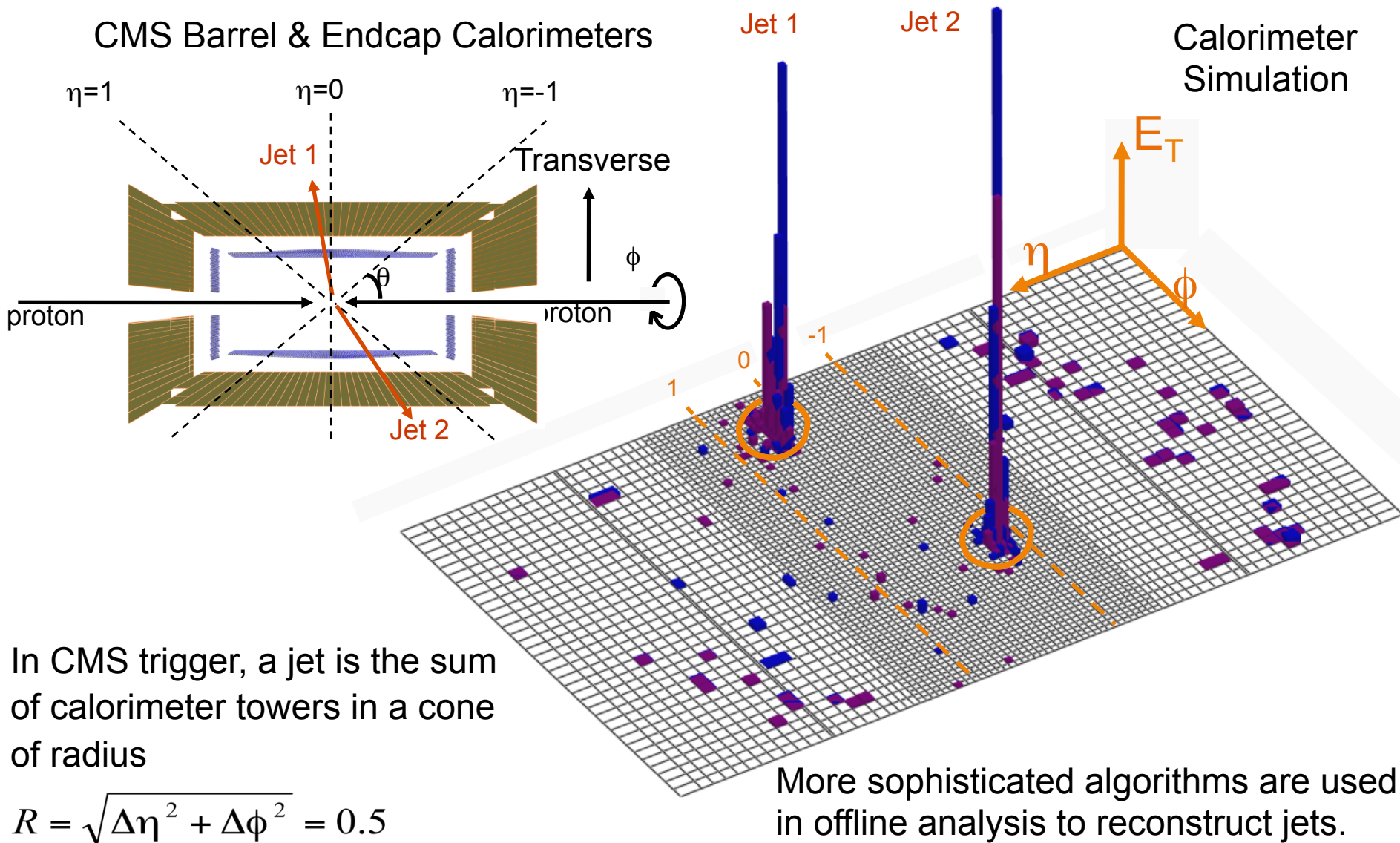


Each final state parton becomes a jet of observable particles.

The process is called dijet production.

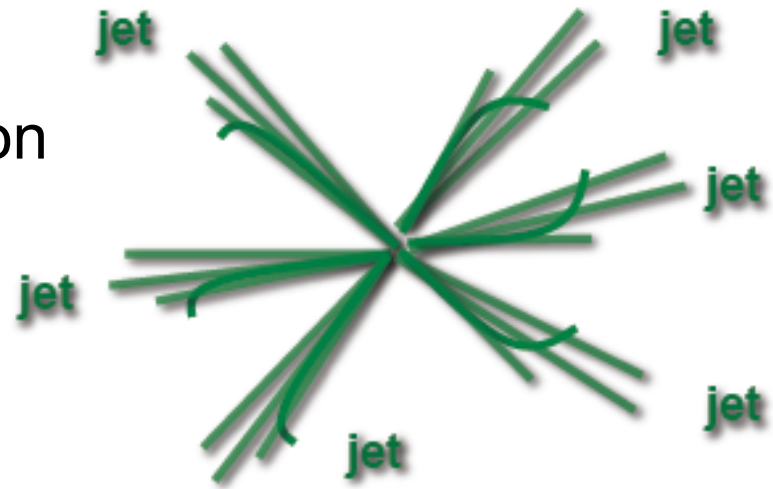


# Experimental observation of Jets



# Why do searches for new physics with jets?

- ❑ Most exotic searches at colliders involve **MET** and/or **leptons/photons**
  - Strong production
  - Electroweak decays
  - Backgrounds suppressed
- ❑ New physics -> **Jets**?
  - Strong production cross-section
  - Strong decays (multi-jet)
  - Backgrounds severe

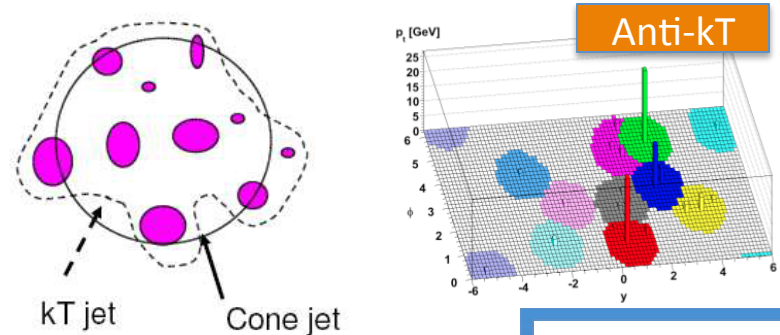


# How are Jets defined?

❑ A *jet algorithm* is a set of mathematical rules that reconstruct unambiguously the properties of a jet.

## ❑ Fixed cone algorithms:

- ✧ Iterative Cone (CMS) / JetClu (ATLAS)
- ✧ Seedless Infrared Safe Cone (SISCone)



## ❑ Successive recombination algorithms:

$$d_{ij} = p_{T,i}^{2p} \quad d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{D^2}$$

p=1	->	k <sub>T</sub> jet algorithm
p=0	->	CA jet algorithm
p=-1	->	“Anti-k <sub>T</sub> ” jet algorithm

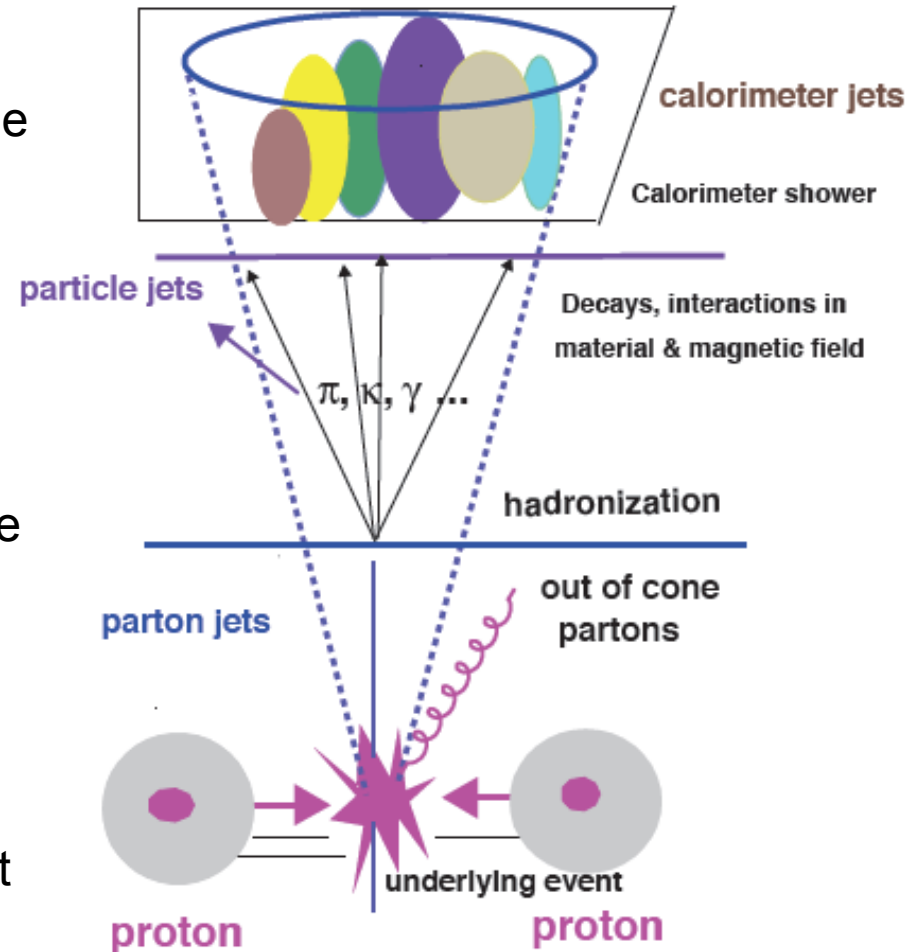
❑ Different inputs to the jet algorithm lead to different types of jets:

- ✧ **Calorimeter jets (CaloJets)**: Clustered from Calorimeter unit (Towers)
- ✧ **Track Jets**: Clustered from charged particle tracks
- ✧ **Jets plus Tracks**: Correct calorimeter jets using momentum of tracks.
- ✧ **Particle Flow Jets**: Clustered from identified particles, reconstructed using all detector components.



# Jet energy scale and does it matter?

- ❑ We do not see quarks and gluons
  - We do not see all stable particles:
  - How do we go from raw inputs (calorimeter / track energy) to the particle level energy? ➡ **Jet Energy Scale**
- ❑ Factors impacting the JES include
  - Calorimeter response
  - Effect of B field (sweeps particles away)
  - Energy offset (i.e. energy not from the hard scattering process)
  - Material in front of the calorimeter
  - Out-of-cone showering
  - Resolution ➡ Unsmearing
- ❑ JES uncertainties typically are the largest systematic uncertainty in jet measurements

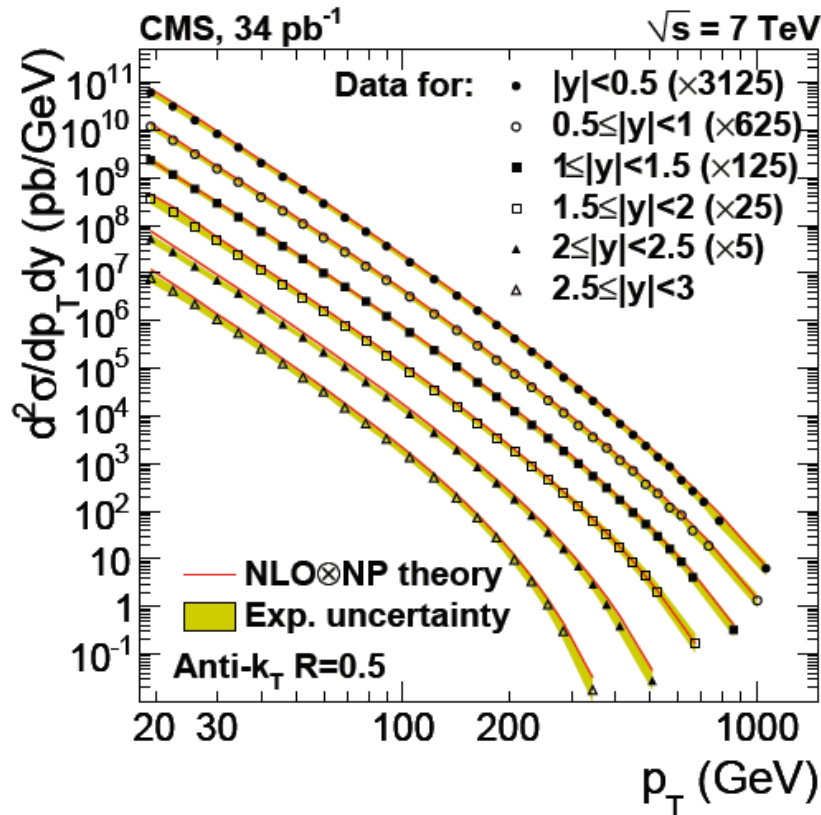


# New Physics searches with (Di)Jets

- ☐ **Search for quark compositeness with dijet angular distributions (\*)**
- ☐ **Search for resonances in dijet angular ratio**
- ☐ **Search for resonances in dijet mass spectrum**
- ☐ **Search for pair produced dijet resonances with four jets**

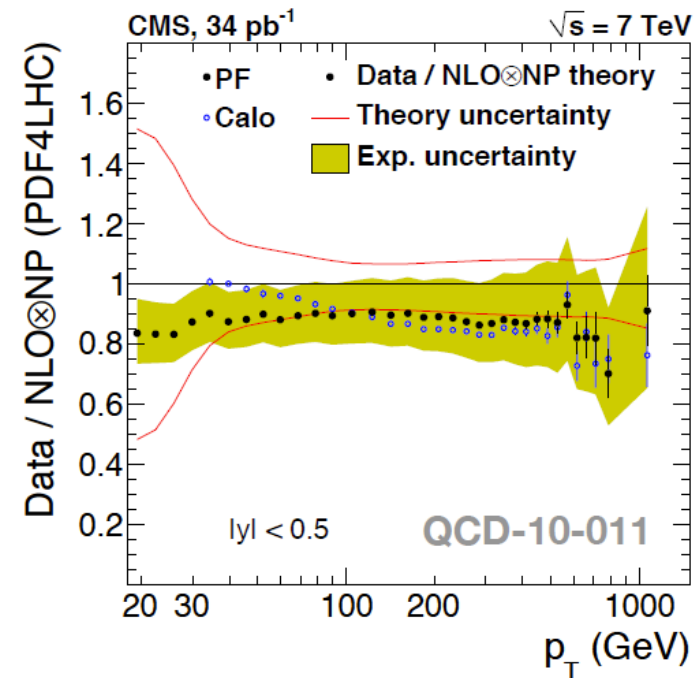
(\*) Will go through one analysis in detail and others have followed similar steps

# First:: Sanity check: Inclusive Jet cross section



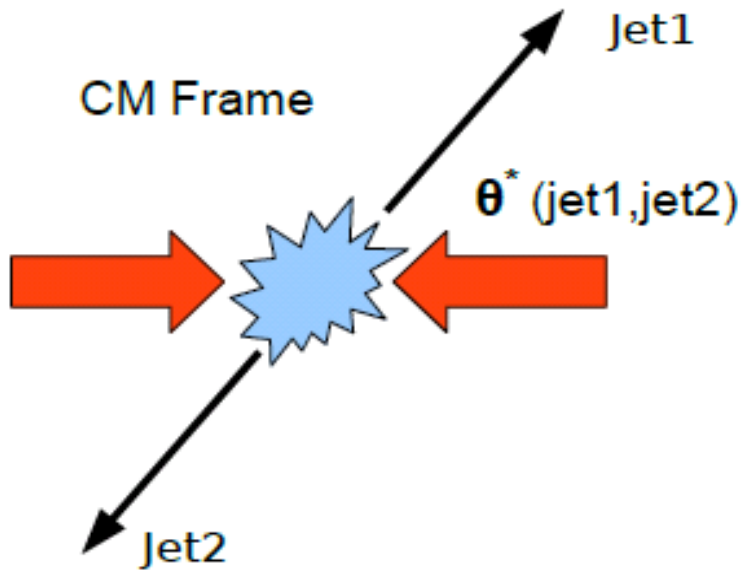
$$\frac{d^2\sigma}{dp_T d|y|} = \frac{C_{\text{unsm}}}{\epsilon \cdot \mathcal{L}} \cdot \frac{N_{\text{jets}}}{\Delta p_T \Delta |y|}$$

- ❑ The cross section measurement extends from 18 GeV to 1.1 TeV in jet  $p_T$
- ❑ Good agreement with NLO theory predictions over 10 orders of magnitude in 6 rapidity bins



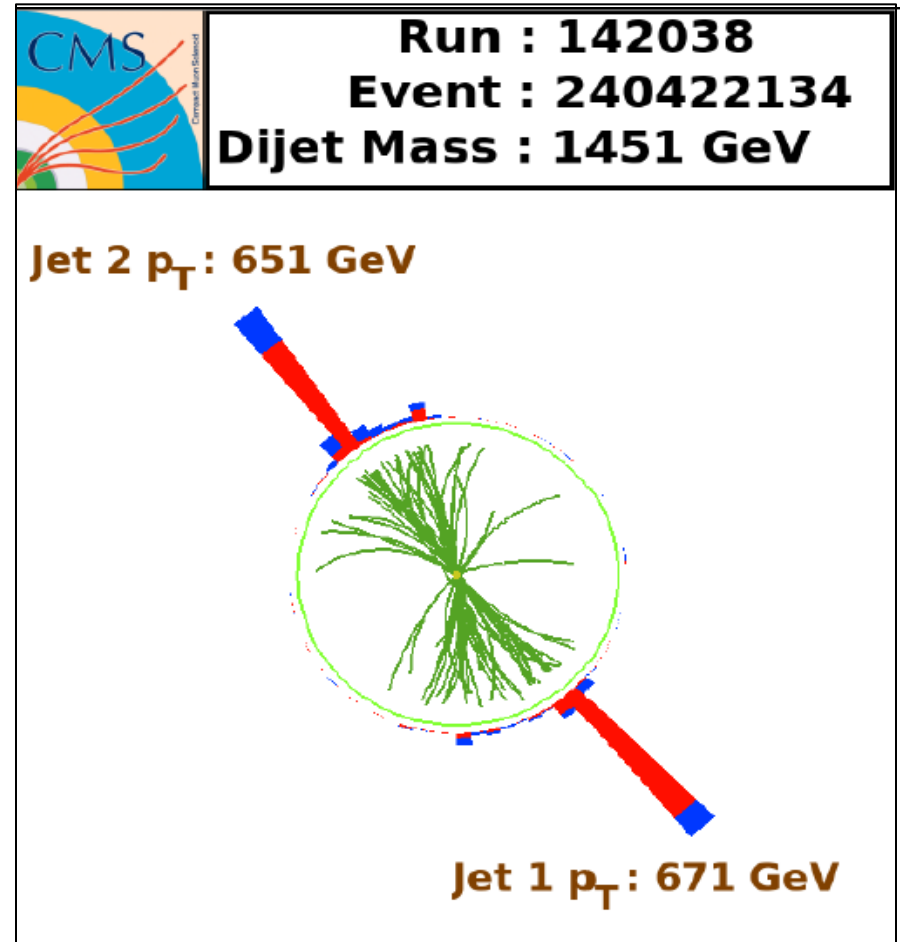


# Dijet system



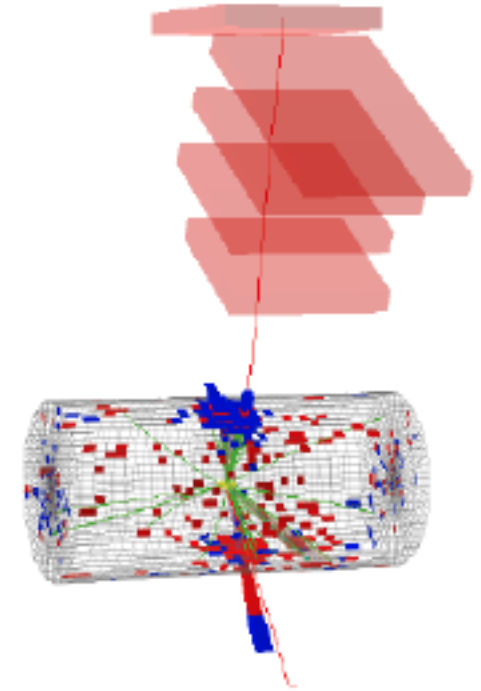
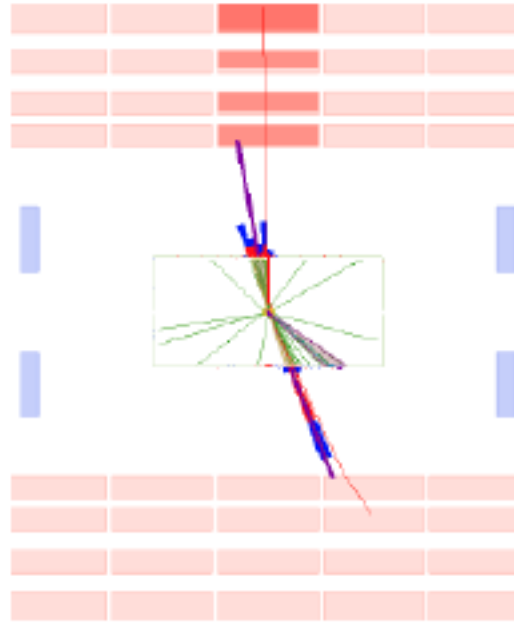
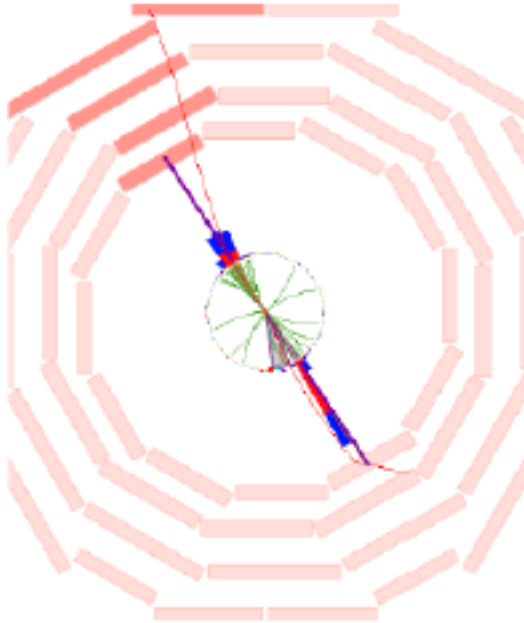
Dijet invariant mass is defined as:

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$



# Highest Mass: $M_{jj} = 3.954$ TeV

Highest  $M_{jj} = 3954$  GeV,  $\chi = 1.75$



167746-314-385009283			
Jet	pT	eta	phi
0	1799.5	0.38	-0.98
1	1799.2	-0.18	2.15
2	36.4	1.05	-1.28
3	15.7	0.82	-0.41

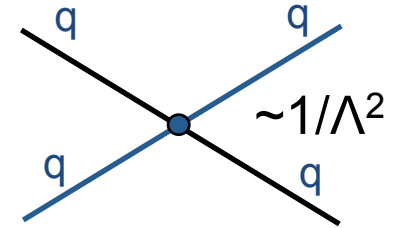
# Dijet angular distributions

$$d\sigma \sim [ \text{QCD} + \text{Interference} + \text{Compositeness} ]$$

$$\alpha_s^2(\mu^2) \frac{1}{\hat{t}^2}$$

$$\alpha_s(\mu^2) \frac{1}{\hat{t}} \cdot \frac{\hat{u}^2}{\Lambda^2}$$

$$\left( \frac{\hat{u}}{\Lambda^2} \right)^2$$

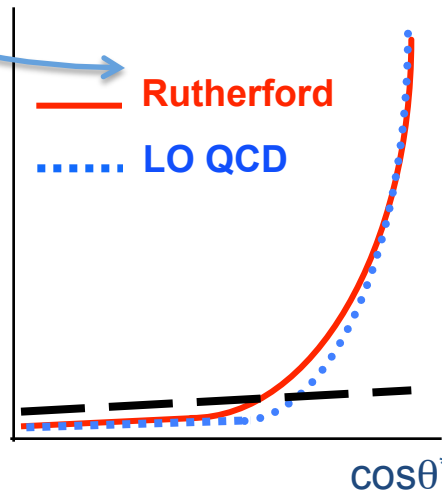
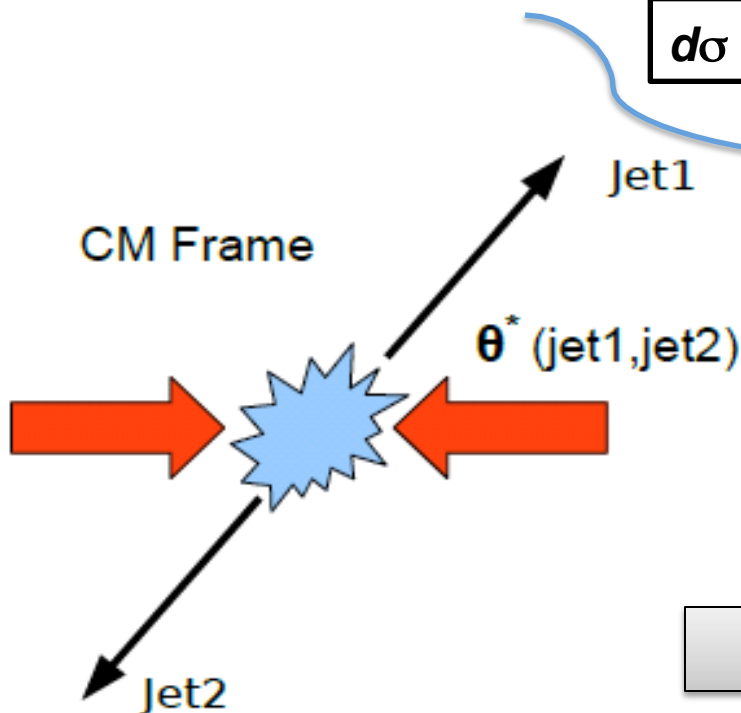


$d\sigma \sim 1/(1-\cos\theta^*)^2$  angular distribution

$d\sigma \sim (1+\cos\theta^*)^2$  angular distribution

$$\sqrt{\hat{s}} \ll \Lambda$$

**Contact interaction**



-- with contact interaction

Can be used to test perturbative QCD

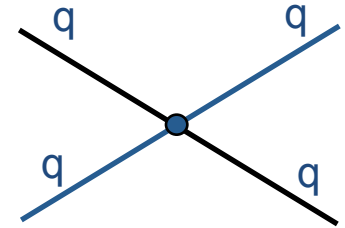
# Dijet angular distributions

$$d\sigma \sim [ \text{QCD} + \text{Interference} + \text{Compositeness} ]$$

$$\alpha_s^2(\mu^2) \frac{1}{\hat{t}^2}$$

$$\alpha_s(\mu^2) \frac{1}{\hat{t}} \cdot \frac{\hat{u}^2}{\Lambda^2}$$

$$\left( \frac{\hat{u}}{\Lambda^2} \right)^2$$



$$\sqrt{\hat{s}} \ll \Lambda$$

$d\sigma \sim 1/(1-\cos\theta^*)^2$  angular distribution

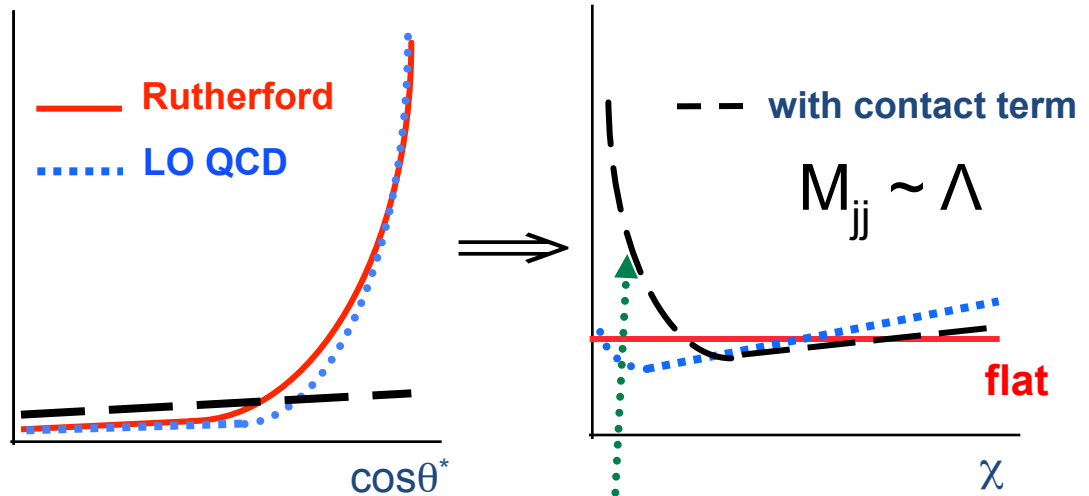
$d\sigma \sim (1+\cos\theta^*)^2$  angular distribution

From  $\cos\theta^*$  variable to  $\chi$

$$y^* = \frac{1}{2} |y_1 - y_2|$$

$$\chi_{dijet} = e^{2y^*} = \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

(for collinear massless partons)



$dN/d\chi$  sensitive to contact interactions



# Quark compositeness models in theory

## □ Color singlet contact interaction models:

$$L_{qq} = \frac{2\pi}{\Lambda^2} [\eta_{LL}(\bar{q}_L \gamma^\mu q_L)(\bar{q}_L \gamma_\mu q_L) + \eta_{RR}(\bar{q}_R \gamma^\mu q_R)(\bar{q}_R \gamma_\mu q_R) + 2\eta_{RL}(\bar{q}_R \gamma^\mu q_R)(\bar{q}_L \gamma_\mu q_L)] ,$$

- Subscripts  $L$  and  $R$  refer to the chiral projections (*helicity*) of the quark fields
- $\eta_{LL}$ ,  $\eta_{RR}$ , and  $\eta_{RL}$  can be 0, +1, or -1.
- The various combinations of  $\eta_{LL}$ ,  $\eta_{RR}$ , and  $\eta_{RL}$  correspond to different Contact Interaction models.

$$\Lambda = \Lambda_{LL}^\pm \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm 1, 0, 0),$$

$$\Lambda = \Lambda_{RR}^\pm \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (0, \pm 1, 0),$$

$$\Lambda = \Lambda_{VV}^\pm \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm 1, \pm 1, \pm 1),$$

$$\Lambda = \Lambda_{AA}^\pm \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm 1, \pm 1, \mp 1),$$

$$\Lambda = \Lambda_{(V-A)}^\pm \text{ for } (\eta_{LL}, \eta_{RR}, \eta_{RL}) = (0, 0, \pm 1).$$

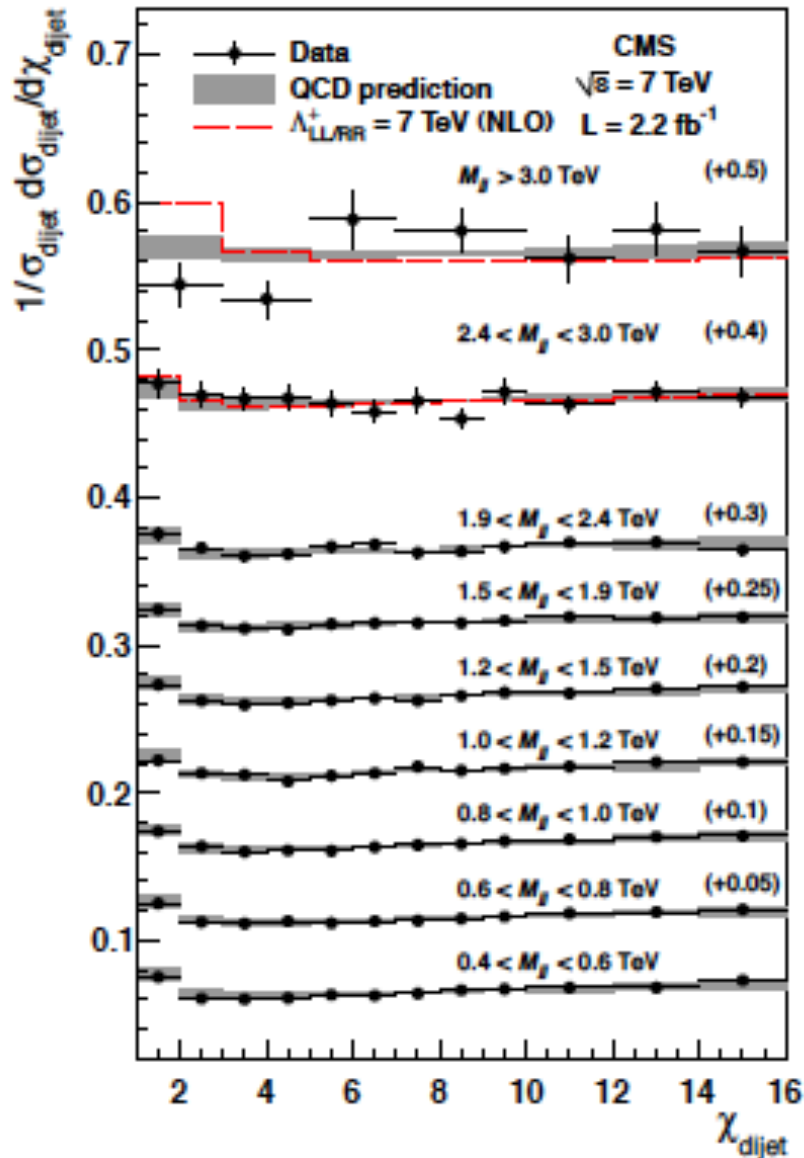
## □ NLO code available for $\Lambda_{LL}^\pm$ (Phys.Rev.Lett. 106 (2011) 142001)

Other models available at LO in Pythia8

- For these models evaluate prediction from “QCD+CI” =  $\text{QCD}_{\text{NLO}} + \text{QCD+CI}_{\text{LO}} - \text{QCD}_{\text{LO}}$

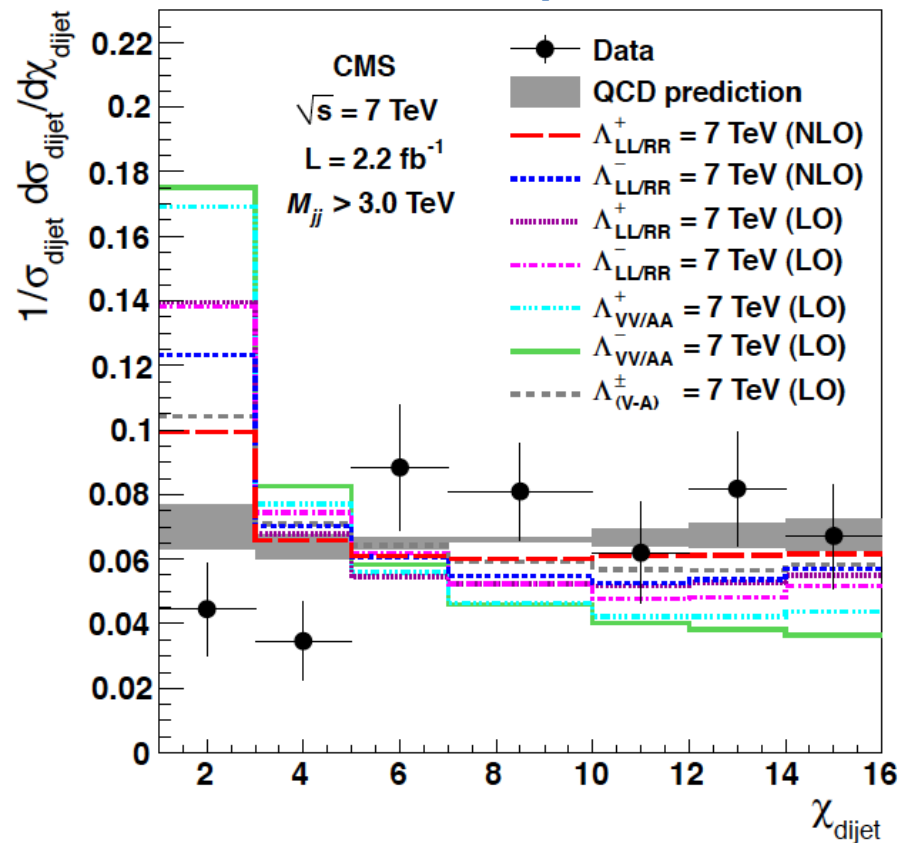
# Dijet angular distributions with $\sqrt{s}=7\text{TeV}$

hep-ex/1202.5535



- Good agreement with p-QCD
- In the highest mass bin the data do not follow any compositeness models

hep-ex/1202.5535



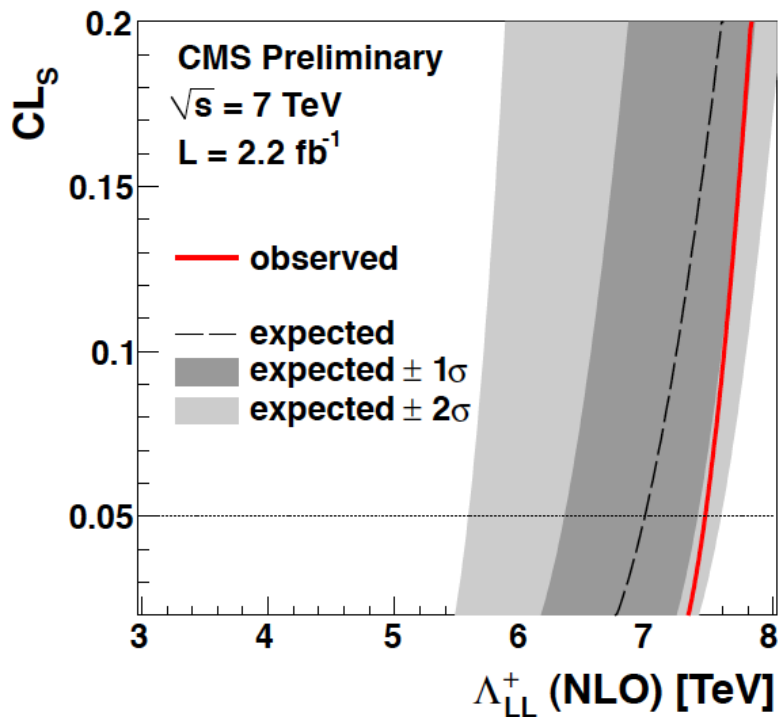
# Various systematics in the dijet angular distribution

Source of Uncertainty	$0.4 < M_{jj} < 0.6 \text{ TeV}$ (%)	$M_{jj} > 3 \text{ TeV}$ (%)
Jet energy scale	1.0	0.3
Jet energy resolution	0.2	0.6
Jet energy resolution tails	0.5	4.6
Unfolding, MC modeling	0.2	4.9
Unfolding, detector simulation	1.3	2.0
Total experimental systematic uncertainty	1.7	7.0
Statistical uncertainty	2.5	31.6
$\mu_r$ and $\mu_f$ scales	5.6	14.9
PDF (CTEQ6.6)	0.5	0.7
Non-perturbative corrections	1.7	1.1
Total theoretical systematic uncertainty	5.9	15.0

- Approximate numbers summarizing the maximal uncertainty on the shape of the  $\chi$ -distributions in two mass bins

# Setting limits to various models

- Without finding an excess of new physics signal events in the  $\chi$ -distributions the existing data is used to set exclusion limits to those models
- Use log likelihood ratio  $\ln\left(\frac{L_{\text{QCD+CI}}}{L_{\text{QCD}}}\right)$  to discriminate between QCD only hypothesis and QCD+CI hypothesis.



- Observed limits stronger than expected limits due to downward fluctuation in highest mass bin

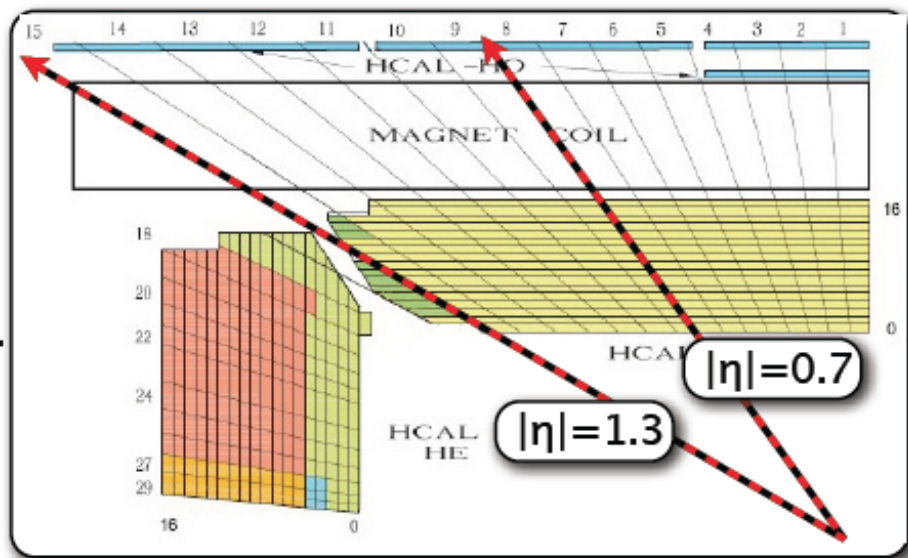
[hep-ex:1202.5535](https://arxiv.org/abs/hep-ex/1202.5535)

CI model	Observed limit (TeV)	Expected limit (TeV)
NLO $\Lambda_{LL/RR}^+$	7.5	$7.0^{+0.4}_{-0.6}$
NLO $\Lambda_{LL/RR}^-$	10.5	$9.7^{+1.0}_{-1.7}$
LO $\Lambda_{LL/RR}^+$	8.4	$7.9^{+0.5}_{-0.7}$
LO $\Lambda_{LL/RR}^-$	11.7	$10.9^{+1.7}_{-2.4}$
LO $\Lambda_{VV/AA}^+$	10.4	$9.5^{+0.5}_{-1.0}$
LO $\Lambda_{VV/AA}^-$	14.5	$13.7^{+2.9}_{-2.6}$
LO $\Lambda_{(V-A)}^\pm$	8.0	$7.8^{+1.0}_{-1.1}$

★ **Most stringent limit to date** (for some models)



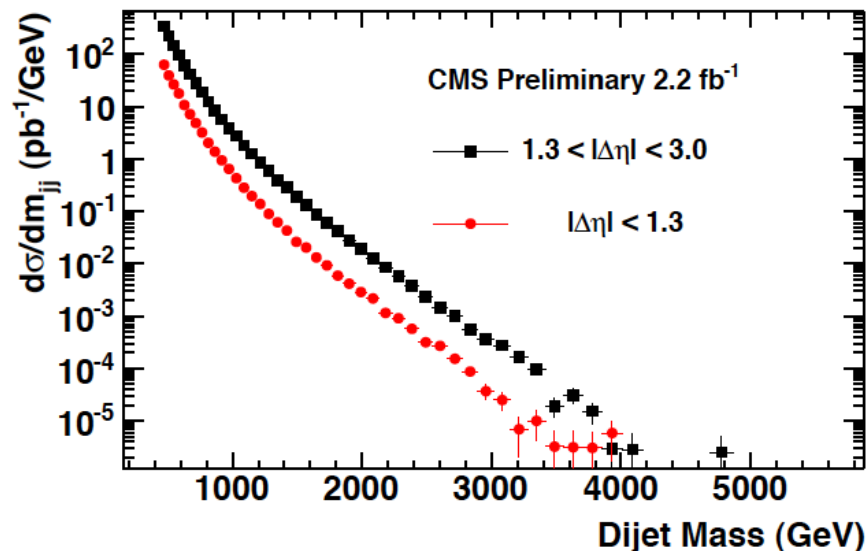
# Dijet centrality ratio



- ❑ QCD dominated by t-channel scattering which produces more forward jets than central jets.
- ❑ Generic contact interaction model<sup>[1]</sup> based on composite quarks enhances isotropic jet production yielding more central jets than does QCD.

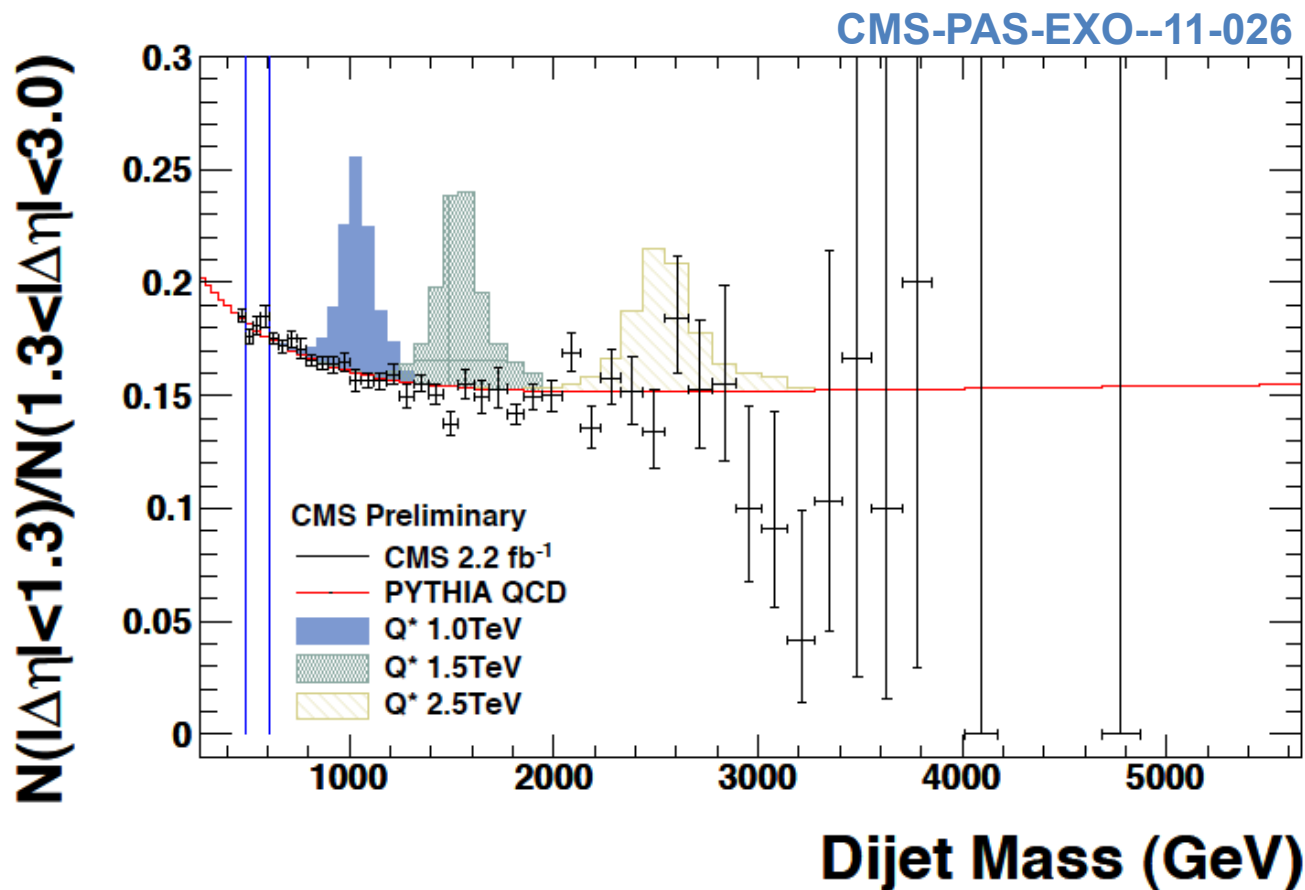
[1] Eichten, Kane, Peskin PRL **50**, 811 (1983).

- ❑ Look for excess of central dijet events compared to forward dijets
- ❑ Measure ratio of inner ( $|\eta| < 0.7$ ) to outer ( $0.7 < |\eta| < 1.3$ ) jets **in bins of dijet mass**.
- ❑ Excess of inner jets implies new physics



- ❑ There are more outer dijets than inner dijets as expected from QCD.

# Dijet centrality ratio - II



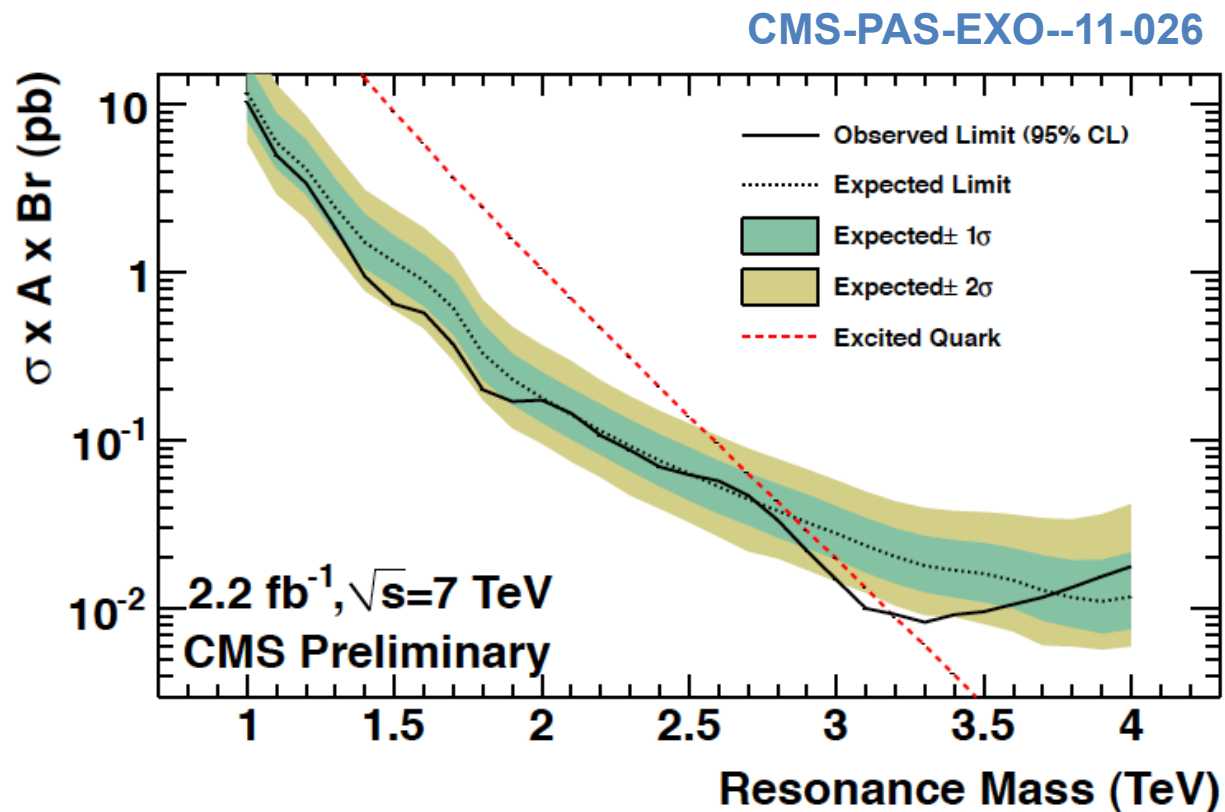
$$R_{\eta} = \frac{N(|\eta| < 0.7)}{N(0.7 < |\eta| < 1.3)}$$

- ❑ Measured dijet angular ratio is fairly flat vs dijet mass, in good agreement with PYTHIA prediction
- ❑ There is no evidence for new physics.
- ❑ Excited quarks from PYTHIA would give excludable peaks up to ~3TeV

# Limits to excited quark model

❑ Limits apply to excited quarks or any isotropically decaying  $qg$  resonance.

❑ Including effects of systematic uncertainties, the limit on an excited quark mass is 2.8 TeV expected and 3.2 TeV observed, very close to limit without systematics.



❑ The data are in good agreement with the standard model background. There is no evidence for a dijet resonance.

❑ We exclude an excited quark of mass of 3.2 TeV at 95% C.L., where the expected limit is 2.8 TeV.

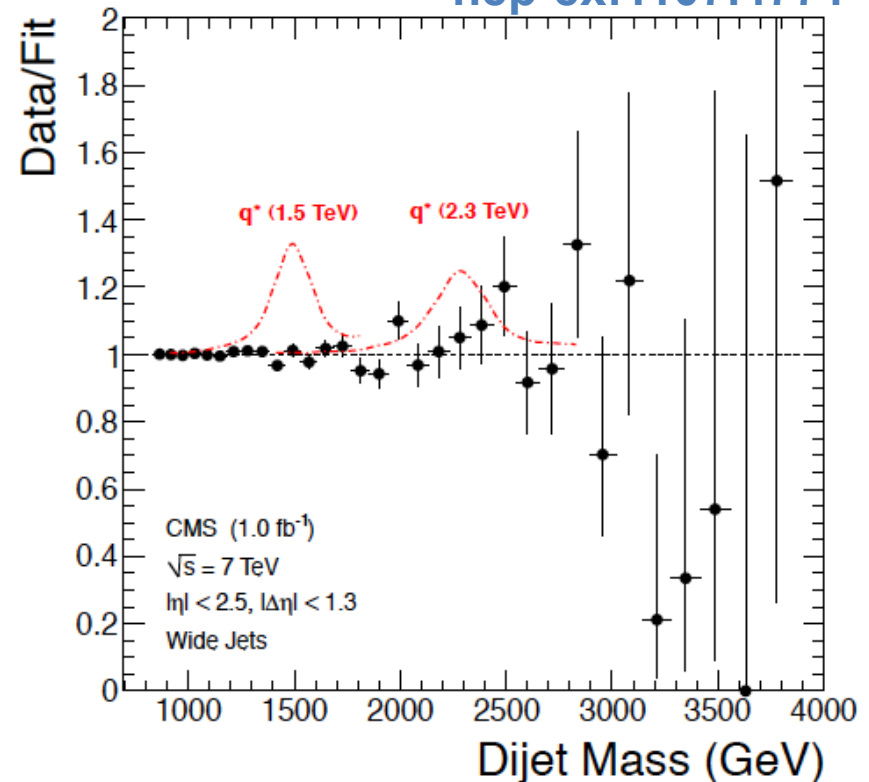
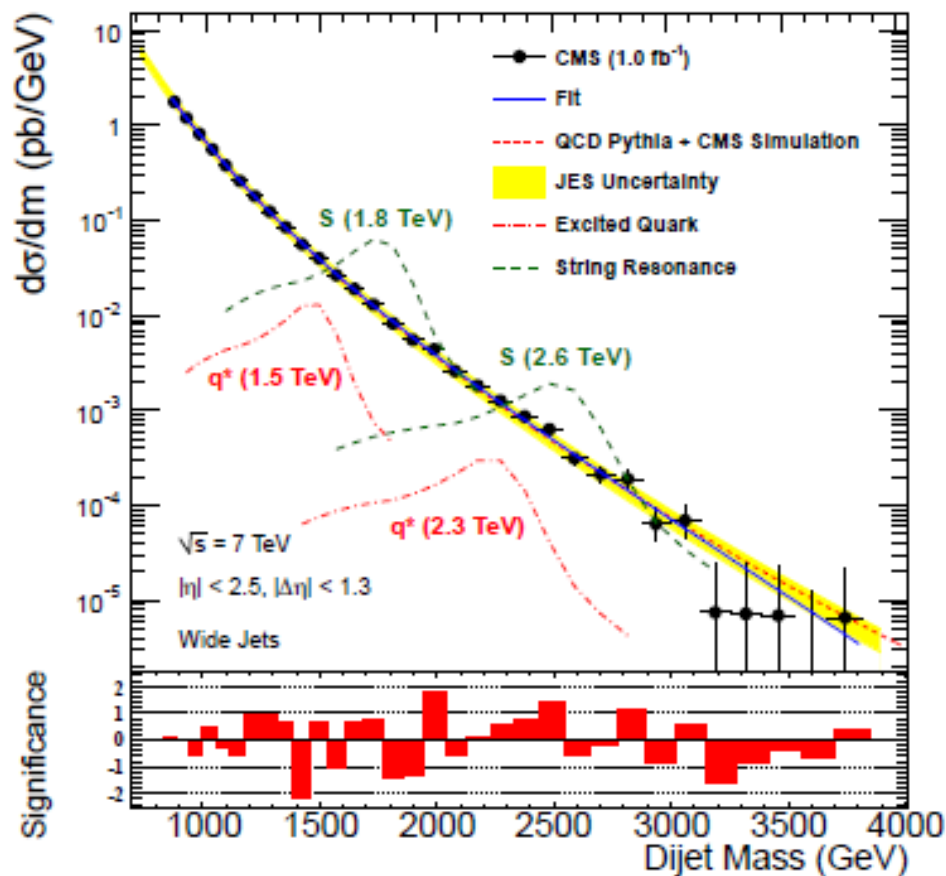
# Models of narrow s-channel dijet resonances

- ❑ **String resonances** (S), which are *Regge excitations* of quarks and gluons in string theory and decay predominantly to  $q\bar{q}$
- ❑ **Scalar diquarks** (D), which decay to  $q\bar{q}$  and  $q\bar{q}q\bar{q}$ , predicted by a grand unified theory based on the  $E_6$  gauge symmetry group
- ❑ Mass-degenerate **excited quarks** ( $q^*$ ), which decay to  $q\bar{q}$ , predicted if quarks are composite objects; the compositeness scale is set to be equal to the mass of the excited quark
- ❑ Axial-vector particles called **axigluons** (A), which decay to  $q\bar{q}$ , predicted in a model where the symmetry group  $SU(3)$  of QCD is replaced by the chiral symmetry  $SU(3)_L \times SU(3)_R$
- ❑ Color-octet **colorons** (C), also decaying to  $q\bar{q}$ , predicted by the flavour-universal coloron model, embedding the  $SU(3)$  symmetry of QCD in a larger gauge group
- ❑ New gauge bosons ( **$W'$  and  $Z'$** ), which decay to  $q\bar{q}$ , predicted by models that include new gauge symmetries; the  $W'$  and  $Z'$  bosons are assumed to have standard model couplings
- ❑ **Randall-Sundrum (RS) gravitons** (G), which decay to  $q\bar{q}$  and  $g\bar{g}$ , predicted in the RS model of extra dimensions; the value of the dimensionless coupling  $\kappa/M_{Pl}$  is chosen to be 0.1



- ❑ The invariant mass spectrum of dijets is predicted to fall steeply and smoothly by Quantum Chromodynamics (QCD).
- ❑ Many extensions of the SM predict the existence of new massive objects that couple to quarks and gluons giving rise to resonances in the dijet mass spectrum.
- ❑ Look for bumps in dijet mass spectrum

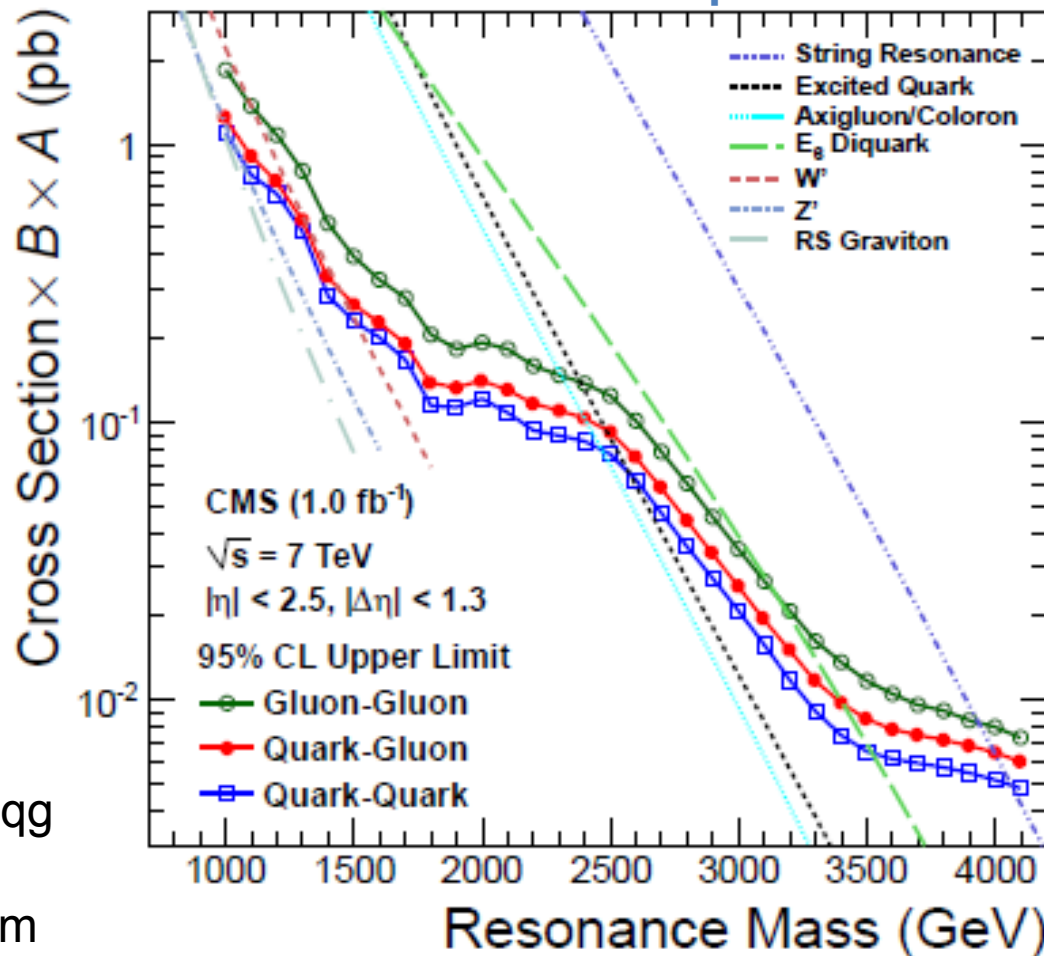
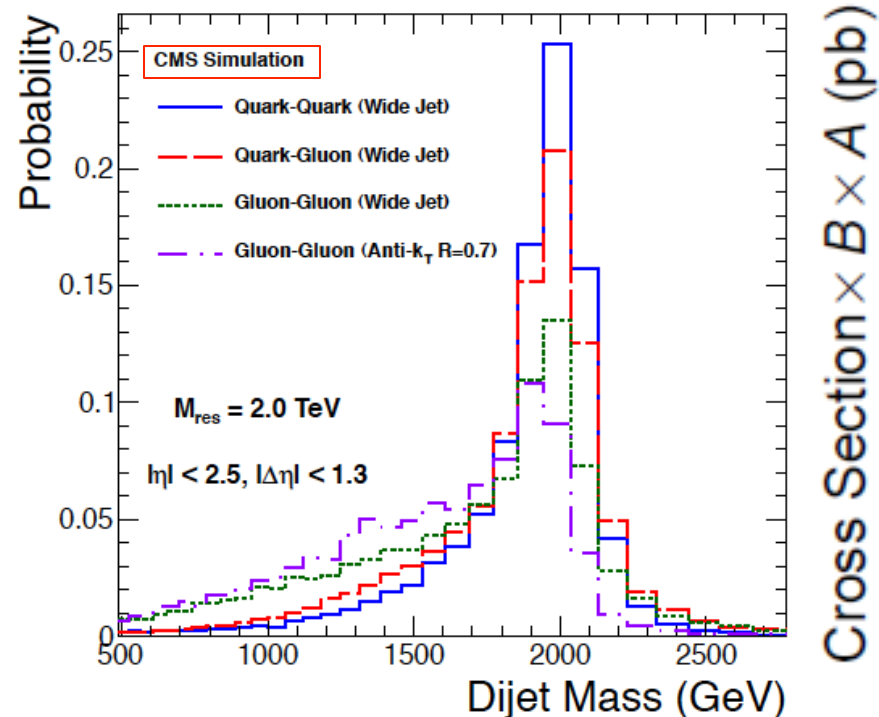
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- ❑ No New Physics is observed with  $1 \text{ fb}^{-1}$
- ❑ Set Limits to various models

# Search for dijet mass resonance - II

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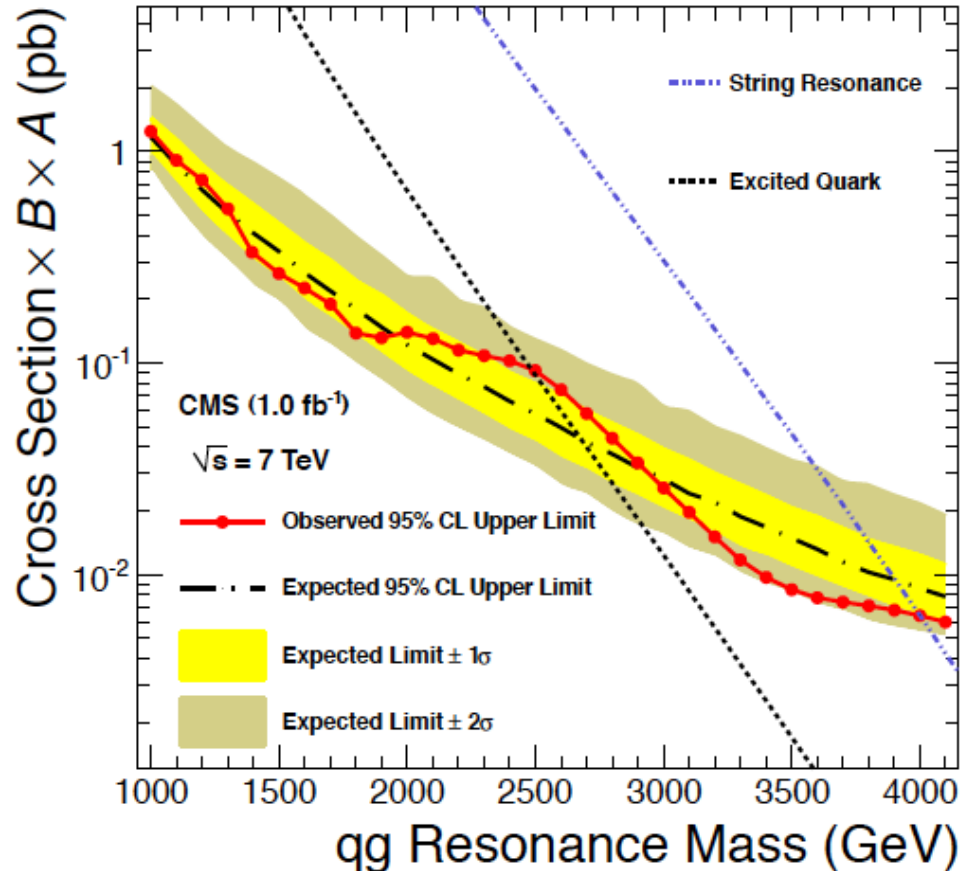
- ❑ Cross section upper limits for qq, qg and gg resonances
- ❑ Compared with cross sections from models to get mass limits

- ❑ 95% CL upper limits to resonance models
- ❑ Wiggles in limit reflect structures in data

# Setting limits to various resonance models

- We use pseudo-experiments to calculate the expected limits

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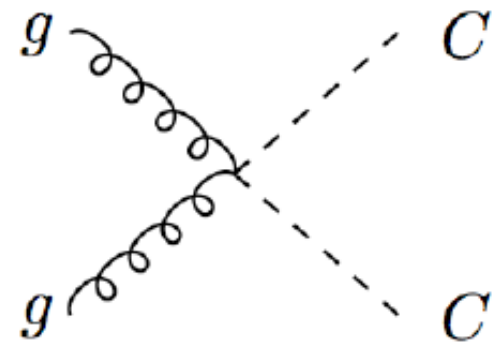
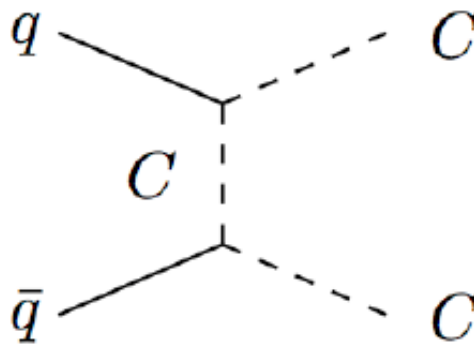
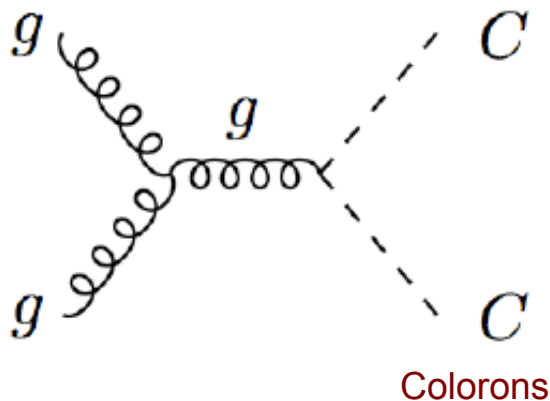
★ **Most stringent limit to date**  
(for some models)

Model	Excluded Mass (TeV)	
	Observed	Expected
String Resonances	4.00	3.90
Excited Quarks	2.49	2.68
E6 Diquarks	3.52	3.28
Axigluons/ Colorons	2.47	2.66
W' Bosons	1.51	1.40

- Statistical fluctuations of data give slightly different observed and expected limits

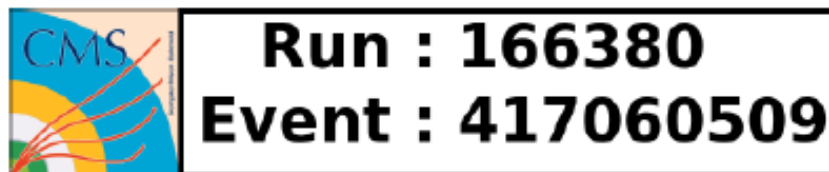
# Pair produced dijet resonance

- ❑ Focus on physics signals from new colored particles, produced strongly in pairs, that decay hadronically to dijets.
- ❑ These signals, which include **pair-produced color-octet scalars or vectors**, can be produced from gluon-gluon ( $gg$ ) or quark-antiquark ( $q\bar{q}$ ) interactions
- ❑ Search for pair-produced narrow resonances each decaying into a pair of jets, using **the paired dijet mass spectrum in four-jet final states**
- ❑ Benchmark model: pair production of **Colorons** [Phys. Lett. **B670**, 119 (2008)] which decay to quark anti-quark pairs ( $q\bar{q}$ ,  $gg \rightarrow CC \rightarrow q\bar{q} q\bar{q}$ )



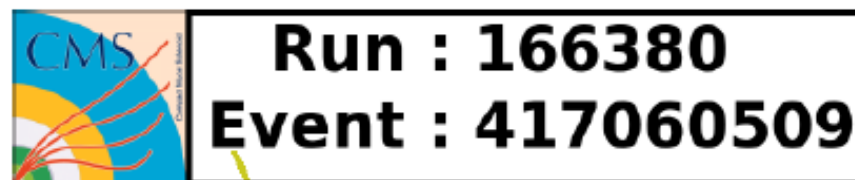
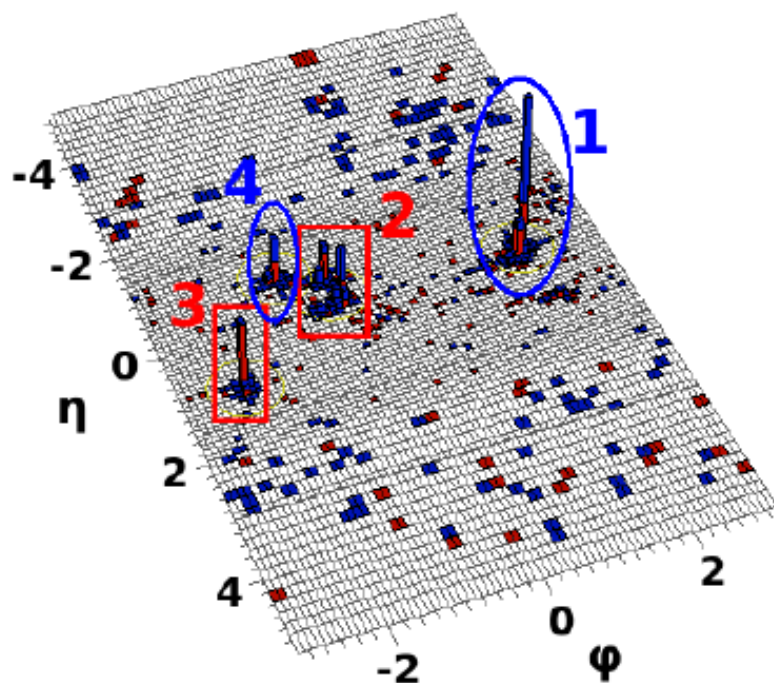


# Paired dijet mass event



**Pair1 (1,4) - mass = 1.075 TeV**

**Pair2 (2,3) - mass = 1.081 TeV**



**Jet 1**

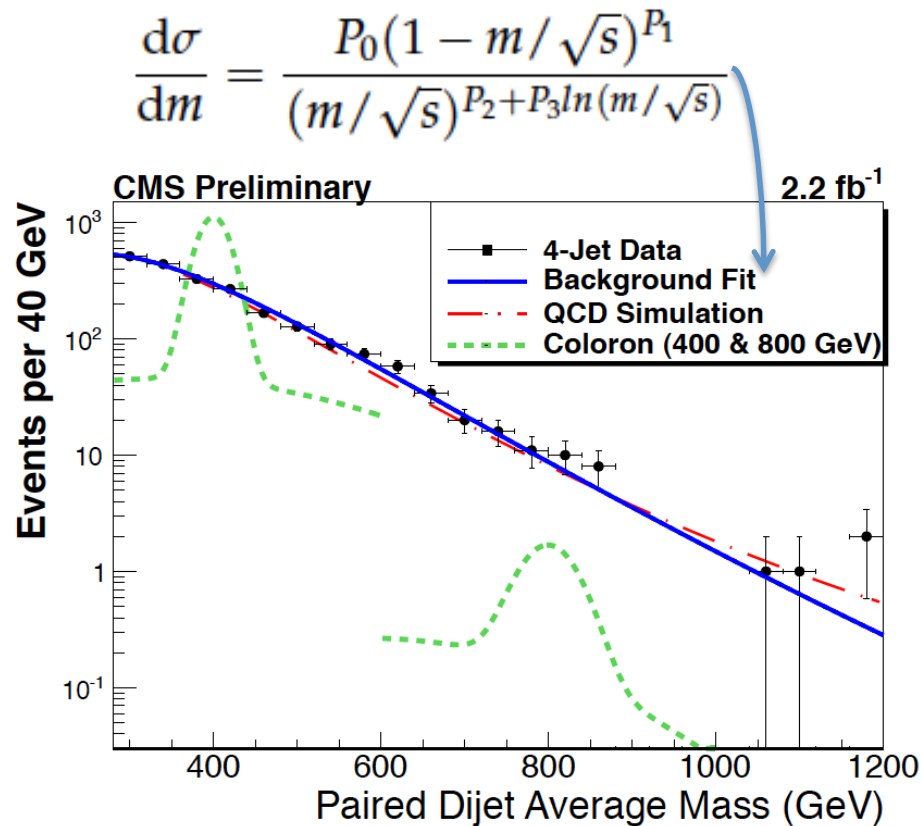
Anti-kt 5 Jet $p_T$	
<b>1</b>	<b>944 GeV</b>
<b>2</b>	<b>771 GeV</b>
<b>3</b>	<b>380 GeV</b>
<b>4</b>	<b>270 GeV</b>

**Jet 3**

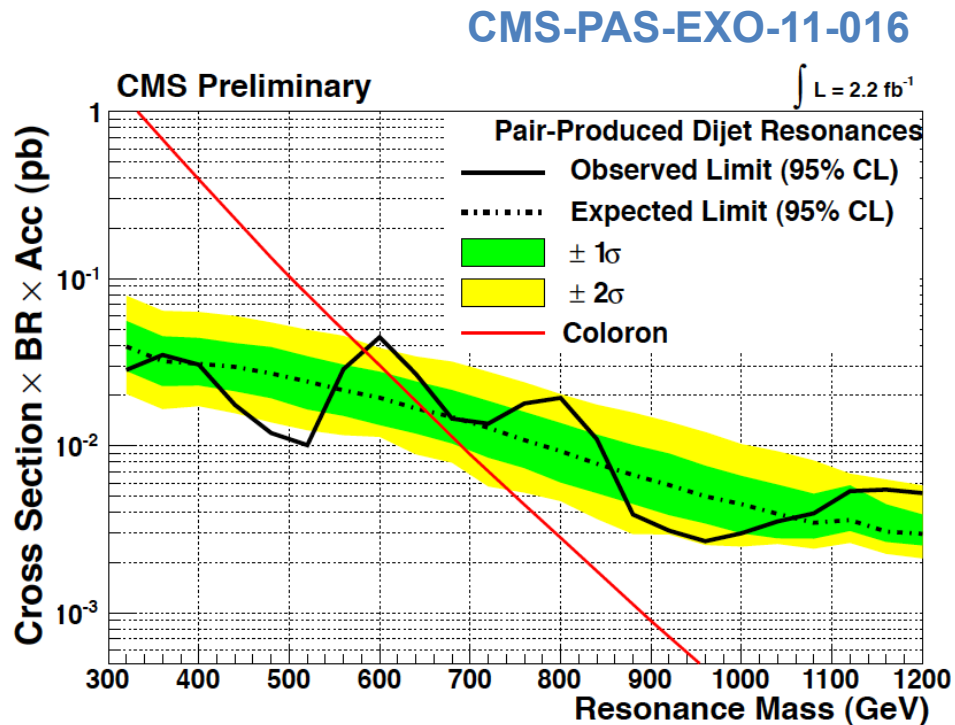
**Jet 4**

**Jet 2**

# Background and signal shapes and limit



- 4-parameter parameterization as in Dijet Resonance search (blue solid).
- Both model the data well
- No evidence for new physics
- Clearly excluded at low resonance mass



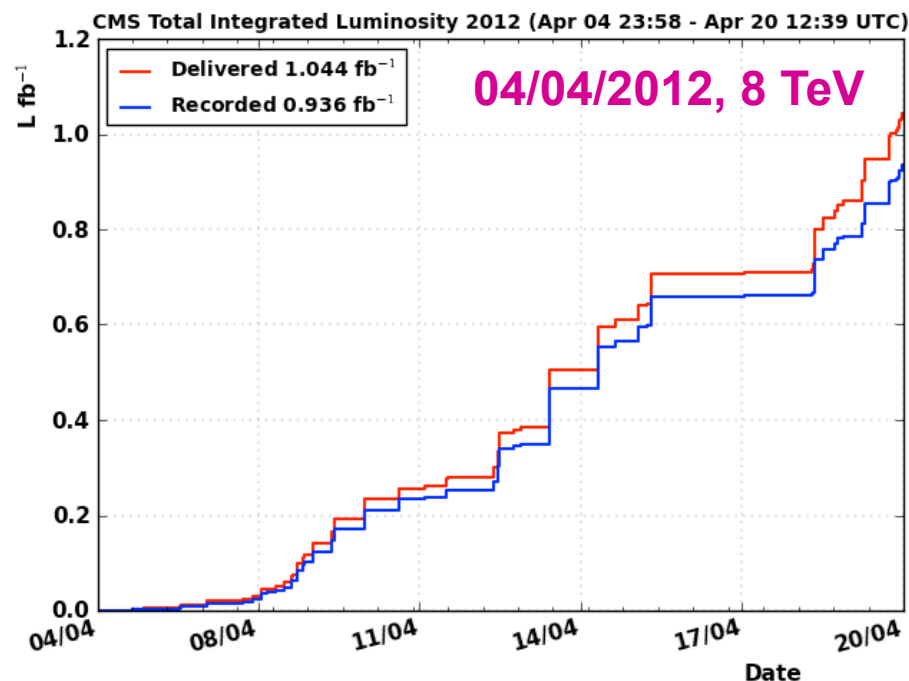
- We exclude pair production of colorons with mass between 320 and 580 GeV at 95% C.L.

# Conclusions

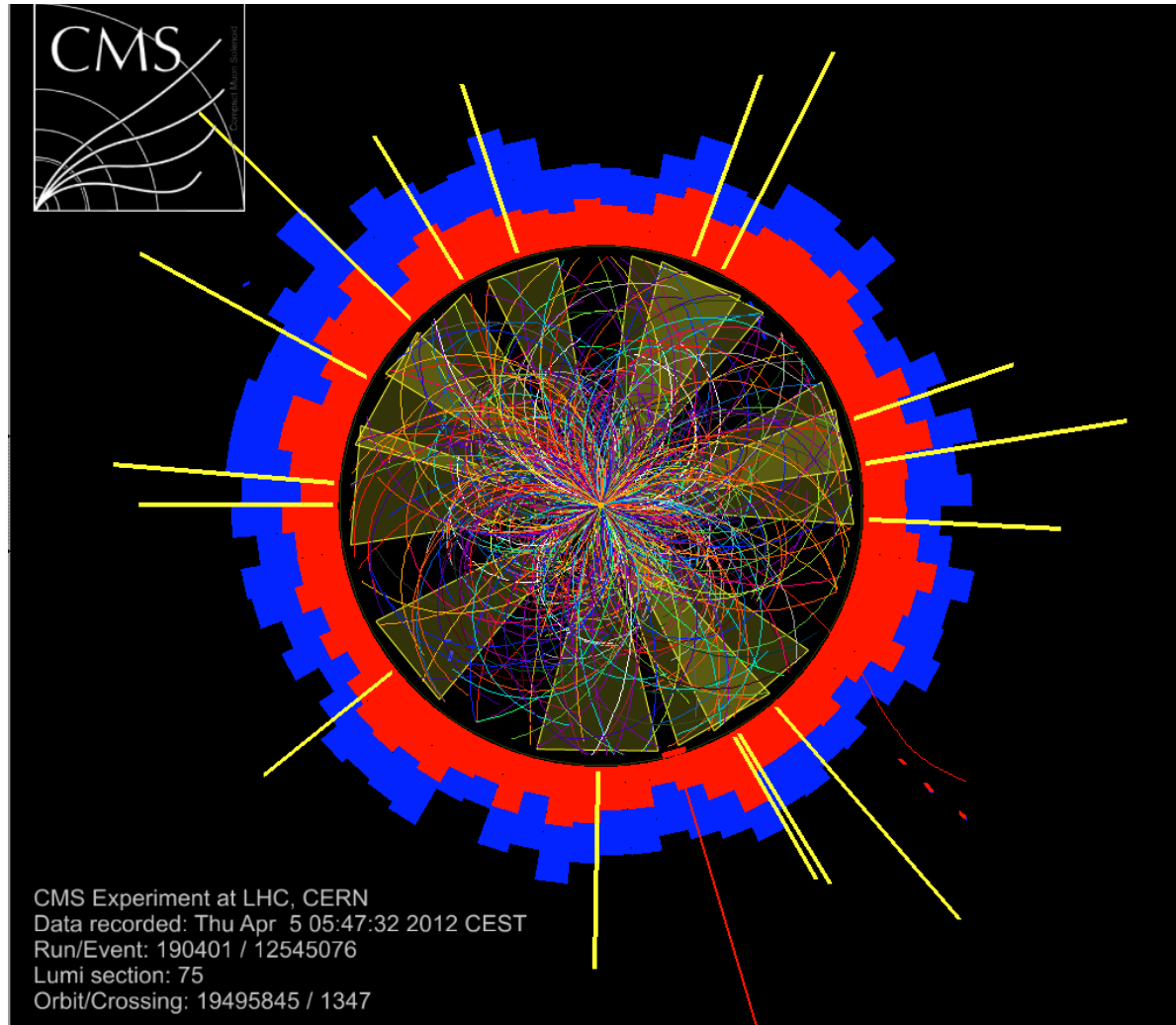
- ❑ Jets are everywhere in CMS
- ❑ For study of any physics if jets are not your signal, then they are certainly your background
- ❑ CMS has done exceptionally well in re-establishing the standard model and now started search for new physics
- ❑ Important results with dijets show CMS's strength in very precise measurement and potential for many more new results
- ❑ Set most stringent limits to many theoretical models of new physics superseding earlier collider physics results
- ❑ LHC era is upon us! Stay tuned for more interesting physics!

# Outlook

- ❑ 2011 data ( $\sqrt{s}=7\text{TeV}$ ) produced many nice analyses searching for new physics signature with jets in the final state
- ❑ We have many analyses with full 2011 data to be converged soon for publication which includes Multijet resonance, searches for compositeness with inclusive jets
- ❑ Searches for extra dimensions with Monojets and Mono photons have also been carried out in CMS – the next week's speaker will talk in details about them
- ❑ 2012 data ( $\sqrt{s}=8\text{TeV}$ ) just started to come
- ❑ The search for new physics is ON
- ❑ With higher Pile Up (PU) the searches will have to be more careful about the effect of PU in the analyses
- ❑ CMS has chosen High priority analyses for 2012 and Dijets are one of them



One of the 1<sup>st</sup>  
recorded 8 TeV  
collisions



Thank you for your attention!